INTERNATIONAL
MARITIME
ORGANIZATION

Second IMO GHG Study 2009

DISCLAIMER
The views and conclusions drawn in this report are those of the scientists writing the report.

CLIMATE CHANGE:
A CHALLENGE FOR IMO TOO!

Published in 2009
by the International Maritime Organization
4 Albert Embankment, London SE1 7SR

Typeset by RefineCatch Limited, Bungay, Suffolk
Printed in the United Kingdom by
CPI Books Limited, Reading RG1 8EX

For bibliographic purposes this document may be cited as: *Second IMO GHG Study 2009*, International Maritime Organization (IMO) London, UK, April 2009; Buhaug, Ø., Corbett, J.J., Endresen, Ø., Eyring, V., Faber, J., Hanayama, S., Lee, D.S., Lee, D., Lindstad, H., Markowska, A.Z., Mjelde, A., Nelissen, D., Nilsen, J., Pålsson, C., Winebrake, J.J., Wu, W., Yoshida, K.

Approval of the Second IMO GHG Study

The Marine Environment Protection Committee, at its fifty-ninth session (July 2009), unanimously approved the Second IMO GHG Study as meeting its Terms of Reference, recognizing that the responsibility for the scientific content of the Study rested with the Consortium that developed it, and agreed that the Study would constitute a significant document and become the paramount reference to the Committee for information in developing and pursuing IMO's strategy to limit and reduce GHG emissions from international shipping. The Marine Environment Protection Committee consists of all IMO Members and is mandated to consider any matter within the scope of the Organization concerned with the prevention and control of pollution from ships, in particular with respect to the adoption of, and amendment to, the comprehensive regulatory framework developed and enacted by IMO. The Committee also considers appropriate measures to facilitate the full and efficient implementation and enforcement of such a framework at the global level.

A message from IMO Secretary-General Efthimios E. Mitropoulos

It is widely acknowledged that an increase in global temperature is altering the complex web of systems that allow life to thrive on earth. From the human perspective, issues such as poverty, socio-economic development, population growth and sustainability are additional factors that serve to complicate finding a viable solution to the problem of human-induced changes in our climate. We stand at a juncture where our words need to be matched by actions, so that climate change will not accelerate its adverse effect on everybody. And the decisions and actions we must take without further delay, will be of paramount importance for generations to come.

International shipping is currently estimated to have emitted 870 million tonnes of CO_2 in 2007, no more than about 2.7% of the global total of that year. That said, mid-range scenarios show that, by 2050, those emissions could grow by a factor of 2 to 3 if no regulations to stem them are enacted.

Successfully addressing climate change will be far from easy; but the consequences of failing to do so are too dire to contemplate. At IMO, we have been, for some time now, energetically pursuing the limitation and reduction of greenhouse gas (GHG) emissions from international shipping, in recognition of the magnitude of the climate change challenge and the intense focus on this topic, both globally and within the Organization.

The Second IMO GHG Study 2009 constitutes a significant scientific work undertaken at the global scale under the auspices of IMO. I would like to congratulate the Consortium of universally-renowned scientific experts for the comprehensive research work carried out and the well-balanced report provided, which will enable the Organization to base its decisions on sound scientific advice. I trust that this Second IMO GHG Study will become the paramount reference for the Organization's Marine Environment Protection Committee in making well-informed and balanced decisions towards the development and adoption of a robust regime to regulate shipping emissions at the global level.

On behalf of the Organization, I applaud and extend my wholehearted thanks also to the Steering Committee for their dedication and support in overseeing the Study - and, not least, I would like to express profound appreciation to: the Governments of Australia, Canada, Denmark, Germany, the Marshall Islands, the Netherlands, Norway, Sweden and the United Kingdom as well as to the Japanese Shipowners' Association, for their financial contributions, which made the Study possible.

The in-hand Study equips IMO with scientific evidence not only to make the right decisions but also to enhance the Organization's credentials as the best placed, and competent regulatory forum to establish an authoritative emissions control regime for international shipping. If, however, we are to succeed in this, the international community must deliver realistic and pragmatic solutions on difficult and complex matters both from a technical standpoint and from a political perspective.

2009 is a crucial year in the world's climate change negotiations, culminating in the convening of an international Conference in Copenhagen, in December, which will pave the way for the future. IMO will bring the findings of this Study to that meeting and I am confident that, following the progress made by the Organization, both in gathering relevant information and translating it into a comprehensive package of technical and operational measures, we will have a positive message to convey to the global community. In return, I very much hope that, as the Kyoto Conference did in 1997, the one in Copenhagen will continue entrusting IMO with the regulation of GHG emissions from international shipping.

Second IMO GHG Study 2009

This study on greenhouse gas emissions from ships has been undertaken by an international consortium led by MARINTEK in partnership with the following institutions:

- MARINTEK, Norway (Coordinator)
- CE Delft, The Netherlands
- Dalian Maritime University, China
- Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR), Germany
- Det Norske Veritas (DNV), Norway
- Energy and Environmental Research Associates (EERA), United States of America
- Lloyd's Register – Fairplay Research, Sweden
- Manchester Metropolitan University, United Kingdom
- Mokpo National Maritime University (MNMU), Korea
- National Maritime Research Institute (NMRI), Japan
- Ocean Policy Research Foundation (OPRF), Japan

The following individuals were the main contributors to the report:

Øyvind Buhaug (Coordinator and Task leader, Emission Reductions), James J. Corbett (Task leader, Emissions and Scenarios), Veronika Eyring (Task leader, Climate Impacts), Øyvind Endresen, Jasper Faber, Shinichi Hanayama, David S. Lee, Donchool Lee, Håkon Lindstad, Agnieszka Z. Markowska, Alvar Mjelde, Dagmar Nelissen, Jørgen Nilsen, Christopher Pålsson, Wu Wanquing, James J. Winebrake, Koichi Yoshida.

Contents

Preface

This study on greenhouse gas emissions from ships was commissioned as an update of the International Maritime Organization's (IMO) *Study of Greenhouse Gas Emissions from Ships* which was published in 2000. It has been prepared on behalf of IMO by an international consortium led by MARINTEK in partnership with the institutions on the previous page. The Steering Committee for the study decided that it should be titled: **Second IMO GHG Study 2009**.

This document presents the final report on the study covering the full scope of work and incorporating changes listed in document MEPC 59/INF.10/Corr.1 as well as some editorial corrections made by the IMO Secretariat.

The main objectives of the study were to assess: (i) present and future emissions from international shipping; (ii) the possibilities for reduction of these emissions through technology and policy; and (iii) impacts on climate from these emissions.

In the course of their efforts, the research team has gratefully received input and comments from a number of individuals and organizations including the International Energy Agency (IEA), the Baltic and International Maritime Council (BIMCO), the International Association of Independent Tanker Owners (INTERTANKO), the Government of Australia, the Government of Greece and the IMO secretariat.

The views and conclusions drawn in this work are those of the scientists writing the report.

It is our hope that this report will be a helpful reference in the work of IMO and its Marine Environment Protection Committee to reduce emissions of greenhouse gases from ships.

Dr. Øyvind Buhaug

Research Manager
Norwegian Maritime Technology Reseach Institute – MARINTEK

Coordinator of the Second IMO GHG Study 2009
Trondheim, Norway, September 2009

List of abbreviations

ACS	Air cavity system
AGWP	Absolute global warming potential
AIS	Automatic identification system
AFFF	Aqueous film-forming foams
AMVER	Automated Mutual-assistance Vessel Rescue system
BC	Black carbon
CBA	Cost–benefit analysis
CDM	Clean development mechanism
CFC	Chlorofluorocarbons
CFD	Computational fluid dynamics
CH_4	Methane
CO	Carbon monoxide
CO_2	Carbon dioxide
COADS	Comprehensive Ocean–Atmosphere Data Set
CORINAIR	Core Inventory of Air Emissions – Programme to establish an inventory of emissions of air pollutants in Europe
ECA	Emission Control Area
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
EJ	Exajoule (10^{19} joules)
EIA	United States Energy Information Administration
EGR	Exhaust gas recirculation (NO_x reduction technology)
EU ETS	European Union Emissions Trading Scheme
FAME	Fatty Acid Methyl Ester (a type of bio-diesel)
FTD	Fischer–Tropsch diesel (a type of synthetic diesel)
GCM	Global climate model
GDP	Gross domestic product
GHG	Greenhouse gas
GT	Gross tonnage
GTP	Global temperature change potential
GWP	Global warming potential
HCFC	Hydrochlorofluorocarbons
HFC	Hydrofluorocarbons
HFO	Heavy fuel oil
HVAC	Heat, ventilation and air conditioning
ICF	International Compensation Fund for GHG emissions from ships
IEA	International Energy Agency
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LNG	Liquefied natural gas
LRFPR	Lloyd's Register – Fairplay Research
LRIT	Long range identification and tracking system
MARPOL	International Convention for the Prevention of Pollution from Ships
MCFC	Molten carbonate fuel cell

MCR	Maximum continuous rating
MDO	Marine diesel oil (distillate marine fuel with possible residual fuel traces)
MEPC	Marine Environment Protection Committee
METS	Maritime emissions trading scheme
MGO	Marine gas oil (distillate marine fuel)
MSD	Medium speed diesel
NO_x	Nitrogen oxides
NMVOC	Non-methane volatile organic compounds
NSV	Net standard volume
O_3	Ozone
OECD	Organization for Economic Co-operation and Development
OPRF	Ocean Policy Research Foundation
PAC	Polycyclic aromatic hydrocarbons
PFOS	Perfluorooctane sulphonates
PM	Particulate matter/material
PM_{10}	Particulate matter/material with aerodynamic diameter 10 micrometres or less
POM	Particulate organic matter/material
RF	Radiative forcing
RPM	Revolutions per minute
RTOC	Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee
SCR	Selective catalytic reduction
SECA	SO_x Emission Control Area
SEMP	Ship efficiency management plan
SF_6	Sulphur hexafluoride
SFOC	Specific fuel oil consumption
SO_x	Sulphur oxides
SOFC	Solid oxide fuel cell
SRES	Special Report on Emissions Scenarios (IPCC)
SSD	Slow speed diesel
TDC	Top dead centre
TEU	Twenty foot equivalent unit
UNCTAD	United Nations Conference on Trade and Development
UNEP	United Nations Environment Programme
UNFCCC	United Nations Framework Convention on Climate Change
VOC	Volatile organic compounds

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 IPCC 2006 Guidelines.
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 IPCC 2006 Guidelines.
Coastwise shipping	Coastwise shipping is freight movements and other shipping activities that are predominantly along coastlines or regionally bound (e.g., passenger vessels, ferries, offshore vessels) as opposed to ocean-going shipping. The distinction is made for the purpose of scenario modelling and is based on ship types, i.e. a ship is either a coastwise or an ocean-going ship.
Ocean-going shipping	This is a term used for scenario modelling. It refers to large cargo-carrying ships engaged in ocean-crossing trade.
Total shipping	This is defined in this report as international and domestic shipping plus fishing. It excludes military vessels.

List of figures

List of tables

1

Executive summary

CONCLUSIONS

- Shipping is estimated to have emitted 1,046 million tonnes of CO_2 in 2007, which corresponds to 3.3% of the global emissions during 2007. International shipping is estimated to have emitted 870 million tonnes, or about 2.7% of the global emissions of CO_2 in 2007.
- Exhaust gases are the primary source of emissions from ships. Carbon dioxide is the most important GHG emitted by ships. Both in terms of quantity and of global warming potential, other GHG emissions from ships are less important.
- Mid-range emissions scenarios show that by 2050, in the absence of policies, carbon dioxide emissions from international shipping may grow by a factor of 2 to 3 (compared to the emissions in 2007) as a result of the growth in shipping.
- A significant potential for reduction of GHG through technical and operational measures has been identified. Together, if implemented, these measures could increase efficiency and reduce the emissions rate by 25% to 75% below the current levels. Many of these measures appear to be cost-effective, although non-financial barriers may discourage their implementation, as discussed in chapter 5.
- A number of policies to reduce GHG emissions from ships are conceivable. This report analyses options that are relevant to the current IMO debate. The report finds that market-based instruments are cost-effective policy instruments with a high environmental effectiveness. These instruments capture the largest amount of emissions under the scope, allow both technical and operational measures in the shipping sector to be used, and can offset emissions in other sectors. A mandatory limit on the Energy Efficiency Design Index for new ships is a cost-effective solution that can provide an incentive to improve the design efficiency of new ships. However, its environmental effect is limited because it only applies to new ships and because it only incentivizes design improvements and not improvements in operations.
- Shipping has been shown, in general, to be an energy-efficient means of transportation compared to other modes. However, not all forms of shipping are more efficient than all other forms of transport.
- The emissions of CO_2 from shipping lead to positive "radiative forcing" (a metric of climate change) and to long-lasting global warming. In the shorter term, the global mean radiative forcing from shipping is negative and implies cooling; however, regional temperature responses and other manifestations of climate change may nevertheless occur. In the longer term, emissions from shipping will result in a warming response as the long-lasting effect of CO_2 will overwhelm any shorter-term cooling effects.
- If a climate is to be stabilized at no more than 2°C warming over pre-industrial levels by 2100 and emissions from shipping continue as projected in the scenarios that are given in this report, then they would constitute between 12% and 18% of the global total CO_2 emissions in 2050 that would be required to achieve stabilization (by 2100) with a 50% probability of success.

BACKGROUND

1.1 The 1997 MARPOL Conference (September 1997) convened by the IMO adopted resolution 8 on "CO_2 emissions from ships". This resolution invited, *inter alia*, the IMO to undertake a study of emissions of GHG from ships for the purpose of establishing the amount and relative percentage of GHG emissions from ships as part of the global inventory of GHG emissions. As a follow-up to the above resolution, the IMO Study of Greenhouse Gas Emissions from Ships was completed and presented to the forty-fifth session of the MEPC (MEPC 45) in June 2000, as document MEPC 45/8.

1.2 MEPC 55 (October 2006) agreed to update the "IMO Study of Greenhouse Gas Emissions from Ships" from 2000 to provide a better foundation for future decisions and to assist in the follow-up to resolution A.963(23). MEPC 56 (July 2007) adopted the Terms of Reference for the updating of the study, which has been given the title "Second IMO GHG Study 2009". This report has been prepared by an international consortium, as set out in the preface to this report.

SCOPE AND STRUCTURE

1.3 As set out in the terms of reference, this study provides estimates of present and future emissions from international shipping. "International shipping" has been defined in accordance with guidelines developed by the Intergovernmental Panel on Climate Change (IPCC). These guidelines divide emissions from waterborne navigation into two primary categories: domestic and international, where "international waterborne navigation" is defined as navigation between ports of different countries. Total estimates that include emissions from domestic shipping and emissions from fishing are also included in this report.

1.4 The study addresses greenhouse gases (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6) and other relevant substances (NO_x, NMVOC, CO, PM, SO_x) that are defined in the terms of reference for this study.

1.5 The report has been organized into the following main parts:

1. annual inventories of emissions of greenhouse gases and other relevant emissions from shipping from 1990 to 2007 (Chapter 3);
2. analysis of the progress in reducing emissions from shipping through implementation of MARPOL Annex VI (Chapter 4);
3. analysis of technical and operational measures to reduce emissions (Chapter 5);
4. analysis of policy options to reduce emissions (Chapter 6);
5. scenarios for future emissions from international shipping (Chapter 7);
6. analysis of the effect of emissions from shipping on the global climate (Chapter 8); and
7. a comparison of the energy efficiency and CO_2 efficiency of shipping compared to other modes of transport (Chapter 9).

EMISSIONS 1990–2007

1.6 The analysis in this report shows that exhaust gas is the dominating source of emissions from shipping. Additionally, emissions originating from leaks of refrigerant and release of volatile organic compounds in conjunction with the transport of crude oil are quantified in this study. Other emissions include diverse sources, such as emissions from testing and maintenance of fire-fighting equipment. These are not considered significant and are not quantified in this report.

1.7 Emissions of exhaust gases from international shipping are estimated in this study, based on a methodology where the total fuel consumption of international shipping is first determined. Emissions are subsequently calculated by multiplying fuel consumption with an emission factor for the pollutant in question.

1.8 Fuel consumption for the year 2007 was estimated by an activity-based methodology. This is a change in methodology compared to the first IMO study on greenhouse gas emissions from ships, published in 2000, which relied on fuel statistics. The investigations that are presented in this study suggest that international fuel statistics would under-report fuel consumption. The difference between the fuel statistics and the activity-based estimate is about 30%.

1.9 Guidebook emission factors from CORINAIR and IPCC were used for all emissions except for NO_x, where adjustments were made to accommodate the effect of the NO_x regulations in MARPOL Annex VI. Estimates of emissions of refrigerants were retrieved from the 2006 United Nations Environmental Programme (UNEP) assessment of refrigerant emissions from transport. The emissions of VOC from crude oil were assessed in this study on the basis of several data sources.

1.10 An estimate of the share of the total emissions of exhaust gases from ships that can be attributed to international shipping was made on the basis of the estimate for total fuel consumption by shipping and statistics for fuel consumption by domestic shipping in 2007. An emissions series from 1990 to 2007 was generated by assuming that ship activity was proportional to data on seaborne transport published by Fearnleys. The estimate of GHG emissions for 2007 is presented in Table 1.1. Emissions of SF_6 and PFCs are considered negligible and are not quantified. Emissions of CO_2 from shipping are compared with global total emissions in Figure 1.1.

Table 1.1 *Summary of GHG emissions from shipping* during 2007*

	International shipping (million tonnes)	Total shipping	
		million tonnes	**CO_2 equivalent**
CO_2	870	1050	1050
CH_4	Not determined*	0.24	6
N_2O	0.02	0.03	9
HFC	Not determined*	0.0004	≤6

* A split into domestic and international emissions is not possible.

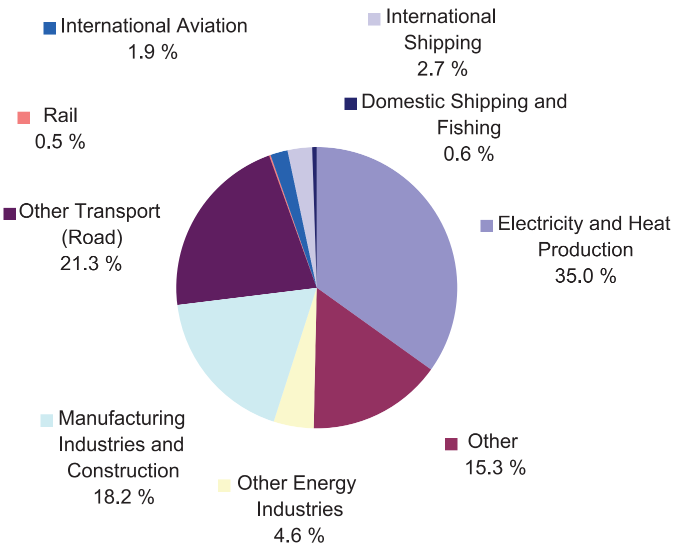


Figure 1.1 *Emissions of CO_2 from shipping compared with global total emissions*

EMISSIONS REDUCTIONS ACHIEVED BY IMPLEMENTATION OF MARPOL ANNEX VI

1.11 Progress to date in reducing emissions was assessed by analysing the reductions in the emissions that are regulated in MARPOL Annex VI.

1.12 Reductions in emissions of ozone-depleting substances (ODSs) from ships have been achieved as a result of several international agreements, including the Montreal Protocol and MARPOL Annex VI. Reductions in these emissions have been estimated on the basis of figures in the 1998 and 2006 reports published by the UNEP Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC). The base year for the 2006 RTOC report is 2003; however, a base year is not available in the 1998 report. Nevertheless, these data indicate the following:

- CFC – 735 tonnes reduction (98%);
- HCFC – 10,900 tonnes reduction (78%); and
- HFC – 415 tonnes increase (315%).

1.13 Emissions of HFC have increased, because HFC are used as a substitute for CFC and HCFC.

1.14 Where emissions of NO_x are concerned, a reduction in emissions of about 12–14% per tonne of fuel consumed has been identified for regulated (Tier I) engines as compared to pre-regulation (Tier 0) engines. In 2007, about 40% of the installed engine power of the world fleet had bee0n built since 1 January 2000 and was thus assumed to be Tier I-compliant. The net reduction in international emissions of NO_x from shipping in 2007 was thus about 6% compared to a no-regulation baseline. However, NO_x emissions from international shipping are estimated to have increased from 16 million tonnes in 2000 to 20 million tonnes in 2007.

1.15 Reductions in SO_x emissions have been estimated for 2008, since this is the first year in which both of the sulphur emission control areas (SECAs) have been fully in force. Based on a set of assumptions, including an average content of sulphur in the fuel that is used in SECAs, in the hypothetical unregulated scenario it is estimated that emissions of sulphur oxides from shipping in the SECA areas had been reduced by about 42%.

1.16 A reduction in emissions of VOC has not been quantified. The most tangible result of implementing regulation 15 in MARPOL Annex VI is the introduction of standardized VOC return pipes, through which tankers can discharge VOC to shore during loading. Most tankers now have this capability, although the frequency of their use is variable.

TECHNOLOGICAL AND OPERATIONAL OPTIONS FOR REDUCTION OF EMISSIONS

1.17 A wide range of options for increasing the energy efficiency and reducing emissions by changing ship design and ship operation has been identified. An overall assessment of the potential of these options to achieve a reduction of CO_2 emissions is shown in Table 1.2. Since the primary gateway to reduction of CO_2 emissions is increased energy efficiency, these reduction potentials generally apply to all emissions of exhaust gases from ships.

Table 1.2 *Assessment of potential reductions of CO_2 emissions from shipping by using known technology and practices*

	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.

1.18 A considerable proportion of the potential abatement appears to be cost-effective at present. However, non-financial barriers may currently limit the adoption of certain measures, as discussed in chapter 5.

1.19 Renewable energy, in the form of electric power generated by solar cells and thrust generated by wind, is technically feasible only as a partial source of replacement power, due to the variable intensity and the peak power of wind and sunlight.

1.20 Carbon dioxide is the most important GHG emission from shipping, and the potential benefits from reducing emissions of the other GHG are small in comparison.

1.21 Fuels with lower life-cycle CO_2 emissions include biofuels and liquefied natural gas (LNG). The use of biofuels on board ships is technically possible; however, use of first-generation biofuels poses some technical challenges and could also increase the risk of losing power (e.g., due to plugging of filters). These challenges are, nevertheless, overshadowed by limited availability and unattractive prices that make this option appear unlikely to be implemented on a large scale in the near future. However, it is believed that LNG will become economically attractive, principally for ships in regional trades within ECAs where LNG is available.

1.22 Emissions of other relevant substances (NO_x, SO_x, PM, CO and NMVOC) as exhaust gas pollutants will be reduced as the energy efficiency of shipping is improved. Long-term reductions in emissions that are mandated or expected from implementation of the revised Annex VI are shown in Table 1.3. Significant reductions in emissions can be achieved by increasing numbers or extending the coverage of Emission Control Areas.

Table 1.3 *Long-term reductions in emissions in the revised MARPOL Annex VI*

	Global	ECA
NO_x (g/kW·h)	15–20%	80%
SO_x* (g/kW·h)	80%	96%
PM (mass)† (g/kW·h)	73%	83%

* Reduction relative to fuel that contains 2.7% sulphur.
† Expected PM reduction arising from change of composition of fuel.

1.23 Future (sulphur) emission control areas ((S)ECAs) will limit the maximum sulphur content of the fuels that are used within these areas to 0.1%. This is a radical improvement from the present-day average of 2.7% of sulphur in residual fuel, although it will still be 100-times higher than the levels of sulphur in automotive diesel fuels (10 ppm, 0.001%). Reductions in emission levels that are significantly beyond the ECA levels indicated in table 1.3 would create a need for stricter fuel-quality requirements.

POLICY OPTIONS FOR REDUCTION OF EMISSIONS

1.24 Many technical and operational measures that may be used to reduce GHG emissions from ships have been identified; however, these measures may not be implemented unless policies are established to support their implementation. A number of policies to reduce GHG emissions from ships are conceivable. This report sets out to identify a comprehensive overview of options. The options that are relevant to the current IMO debate are analysed in detail. These options are:

- a mandatory limit on the Energy Efficiency Design Index (EEDI) for new ships;
- mandatory or voluntary reporting of the EEDI for new ships;
- mandatory or voluntary reporting of the Energy Efficiency Operational Indicator (EEOI);
- mandatory or voluntary use of a Ship Efficiency Management Plan (SEMP);
- mandatory limit on the EEOI value, combined with a penalty for non-compliance;
- a Maritime Emissions Trading Scheme (METS); and
- a so-called International Compensation Fund (ICF), to be financed by a levy on marine bunkers.

1.25 The analysis of the options is based on the criteria for a coherent and comprehensive future IMO regulatory framework on GHG emissions from ships, developed by MEPC 57. Based on these criteria, the following qualitative conclusions can be drawn with respect to options being discussed within IMO at present:

1. A mandatory limit on Energy Efficiency Design Index (EEDI) for new ships appears to be a cost-effective solution that can provide a strong incentive to improve the design efficiency of new ships. The main limitation of the EEDI is that it only addresses ship design; operational measures are not considered. This limits the environmental effectiveness. The effect is also limited, in the sense that it applies only to new ships.
2. Mandatory and/or voluntary reporting of either the EEDI or the EEOI would have no environmental effect in itself. Rather, environmental effectiveness and cost-effectiveness would depend on incentive schemes being set up to make use of the information. The assessment of the large number of conceivable incentive schemes was beyond the scope of this report.
3. The Ship Efficiency Management Plan (SEMP) appears to be a feasible approach to increase awareness of cost-effective measures to reduce emissions. However, since this instrument does not require a reduction of emissions, its effectiveness will depend on the availability of cost-effective measures to reduce emissions (i.e. measures for which the fuel savings exceed the capital and operational expenditures). Likewise, it will not incentivize innovation and R&D beyond the situation of "business as usual".
4. A mandatory limit on EEOI appears to be a cost-effective solution that can provide a strong incentive to reduce emissions from all ships that are engaged in transport work. It incentivizes both technical and operational measures. However, this option is technically very challenging, due to the difficulties in establishing and updating baselines for operational efficiency and in setting targets.
5. Both the Maritime Emission Trading Scheme (METS) and the International Compensation Fund for GHG Emissions from Ships (ICF) are cost-effective policy instruments with high environmental effectiveness. They have the largest amount of emissions within their scope, allow all measures in the shipping sector to be used and can offset emissions in other sectors. These instruments provide strong incentives to technological change, both in operational technologies and in ship design.
6. The environmental effect of the METS is an integral part of its design and will therefore be met. In contrast, part of the environmental effect of the ICF depends on decisions about the share of funds that will be spent on buying emission allowances from other sectors. With regard to cost-effectiveness, incentives to technological change and feasibility of implementation, both policy instruments seem to be quite similar.

SCENARIOS FOR FUTURE EMISSIONS FROM INTERNATIONAL SHIPPING

1.26 Future emissions of CO_2 from international shipping were estimated on the basis of a relatively simple model, which was developed in accordance with well-established scenario practice and methodology. The model incorporates a limited number of key driving parameters, as shown in Table 1.4.

Table 1.4 *Driving variables used for scenario analysis*

Category	Variable	Related elements
Economy	Shipping transport demand (tonne-miles/year)	Population, global and regional economic growth, modal shifts, shifts in sectoral demand
Transport efficiency	Transport efficiency (MJ/tonne-mile) – depends on fleet composition, ship technology and operation	Ship design, advances in propulsion, vessel speed, regulations aimed at achieving other objectives but that have consequences for emissions of GHG
Energy	Carbon fraction of the fuel that is used by shipping (g of C/MJ of fuel energy)	Cost and availability of fuels (e.g., use of residual fuel, distillates, biofuels, or other fuels)

1.27 In this study, carbon emissions are explicitly modelled as a parameter of the scenario. Other levels of pollutant emissions are calculated on the basis of energy consumption and MARPOL regulations. Scenarios are based on the framework for global development and storylines that have been developed by the Intergovernmental Panel on Climate Change (IPCC) in the Special Report on Emission Scenarios (SRES).

1.28 A hybrid approach, considering both historic correlations between economic growth and trade as well as analysis considering regional shifts in trade, increased recycling, and new transport corridors, has been employed, *inter alia*, to derive the projections of future demand for transport.

1.29 No regulations regarding CO_2 or fuel efficiency have been assumed, and the improvement in efficiency over time reflects improvements that would be cost-effective in the various scenarios rather than the ultimate technological potential.

1.30 Assumptions about future use of fuel reflect that the availability of energy in the SRES scenarios would permit the continued use of oil-based fuels until 2050 for shipping. Therefore, in these scenarios, in which there is non-regulation of GHG emissions, the move from oil-derived fuels would have to be motivated by economic factors. The effect of MARPOL Annex VI on the fuel that is used is considered.

1.31 Scenarios are modelled from 2007 to 2050. The main scenarios are named A1FI, A1B, A1T, A2, B1 and B2, according to terminology from the IPCC Special Report on Emission Scenarios (SRES). These scenarios are characterized by global differences in population, economy, land-use and agriculture which are evaluated against two major tendencies: (1) globalization versus regionalization and (2) environmental values versus economic values. The background for these scenarios is discussed in chapter 7 of this report.

1.32 Annual increases of CO_2 emissions, in the range of 1.9–2.7%, are found in base scenarios, with extreme scenarios indicating increases of 5.2% and –0.8%, respectively. The increase in emissions is driven by the expected growth in seaborne transport. The scenarios with the lowest emissions show reductions in CO_2 emissions in 2050 compared to emissions during 2007. Results from the scenarios are shown in Figure 1.2.

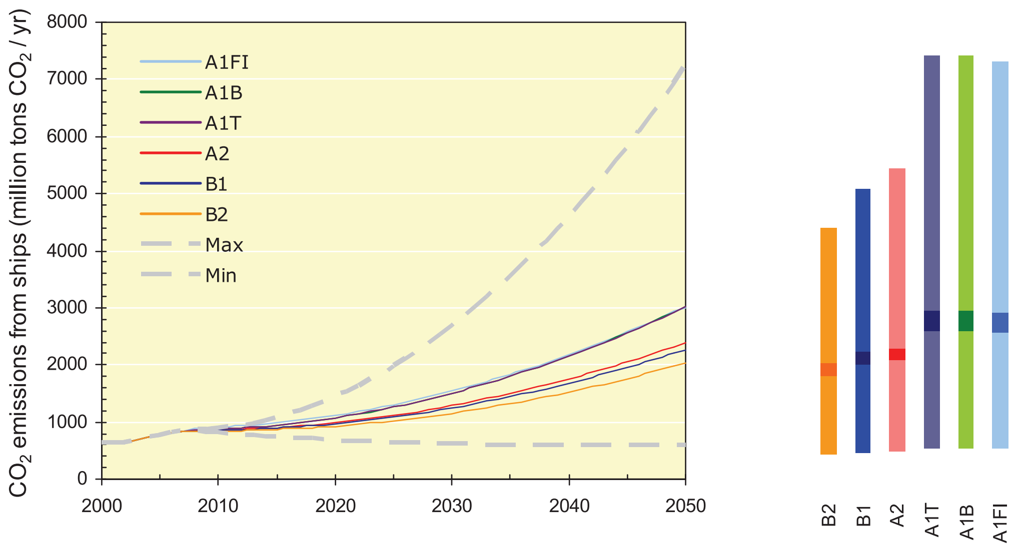


Figure 1.2 *Trajectories of the emissions from international shipping. Columns on the right-hand side indicate the range of results for the scenarios within individual families of scenario.*

CLIMATE IMPACT

1.33 A detailed analysis of the climate impacts of emissions from ships was performed, using state-of-the-art modelling and references to and comparison with other relevant research. Emissions from international shipping produce significant impacts on atmospheric composition, human health and climate; these are summarized below:

1. Increases in well-mixed GHGs, such as CO_2, lead to positive "radiative forcing,"[1] (RF) and to long-lasting global warming.
2. For 2007, the RF from CO_2 from shipping was calculated to be 49 mW m^{-2}, contributing approximately 2.8% of total RF from anthropogenic CO_2 in 2005.
3. For a range of 2050 scenarios, the RF of CO_2 from shipping was calculated to be between 99 and 122 mW m^{-2}, bounded by a minimum/maximum uncertainty range (from the scenarios) of 68 mW m^{-2} and 152 mW m^{-2}.
4. The total RF for 2007 from shipping was estimated to be −110 mW m^{-2}, dominated by a rather uncertain estimate of the indirect effect (−116 mW m^{-2}) and not including the possible positive RF from the interaction of black carbon with snow, which has not yet been calculated for ship emissions. We also emphasize that CO_2 remains in the atmosphere for a long time and will continue to have a warming effect long after it was emitted. This has been demonstrated here by showing how the residual effects of emissions from shipping prior to 2007 turn from a negative effect on temperature to a positive effect. By contrast, sulphate has a residence time in the atmosphere of approximately 10 days, and the duration of response of the climate to sulphate is of the order of decades, whilst that of CO_2 is of the order of centuries to millennia.
5. Simple calculations of global means have been presented here for RF and temperature response, and are in agreement with other studies in the literature. As highlighted by others, global mean temperature response is only a first-order indicator of climate change. Calculations presented here show that the radiative forcing from shipping has a complex spatial structure, and there is evidence from other, more general, studies of indirect cloud-forcing effects that significant changes in precipitation patterns may result from localized negative RFs, even if the localized temperature response is not so variable. Such alterations in precipitation, even from negative forcing, constitute climate change. This is a complex subject, and more work on this aspect is needed.
6. While the control of emissions of NO_x, SO_2 and particles from ships will have beneficial impacts on air quality, acidification and eutrophication, reductions of emissions of CO_2 from all sources (including ships and other freight modes) will be required to reduce global warming. Moreover, a shift to cleaner combustion and cleaner fuels may be enhanced by a shift to technologies that lower the emissions of CO_2.
7. Climate stabilization will require significant reductions in future global emissions of CO_2. The projected emissions from shipping for 2050 that have been developed for this work – which are based on SRES non-climate intervention policy assumptions – constitute 12% to 18% of the WRE450 stabilization scenario, which corresponds to the total permissible global emissions of CO_2 in 2050 if the increase in global average temperature is to be limited to 2°C with a probability greater than 50%.

COMPARISON OF EMISSIONS OF CO_2 FROM SHIPS WITH EMISSIONS FROM OTHER MODES OF TRANSPORT

1.34 The ranges of CO_2 efficiency of various forms of transport were estimated, using actual operating data, transport statistics and other information. The efficiency of ships is compared with that of other

1 a common metric to quantify impacts on climate from different sources is "radiative forcing" (RF), in units of W/m^2, since there is an approximately linear relationship between global mean radiative forcing and change in global mean surface temperature. RF refers to the change in the Earth–atmosphere energy balance since the pre-industrial period. If the atmosphere is subject to a positive RF from, for example, the addition of a greenhouse gas such as CO_2, the atmosphere attempts to re-establish a radiative equilibrium, resulting in a warming of the atmosphere.

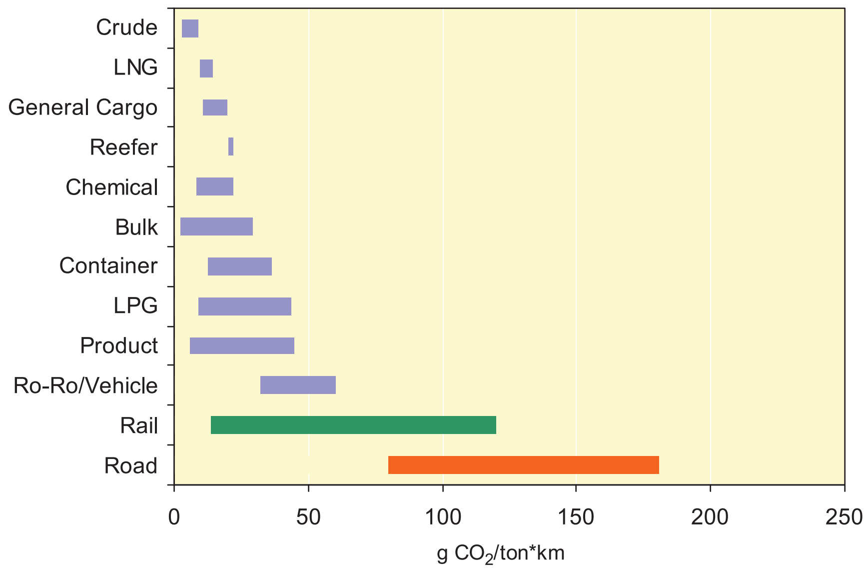


Figure 1.3 Typical ranges of CO_2 efficiencies of ships compared with rail and road transport

modes of transport in Figure 1.3. Efficiency is expressed as mass of CO_2 per tonne-kilometre, where the mass of CO_2 expresses the total emissions from the activity and "tonne-kilometre" expresses the total transport work that is done. The ranges that have been plotted in the figure show the typical average range for each of them. The figure does not indicate the maximum (or minimum) efficiency that may be observed.

2

Introduction to shipping and its legislative framework

2.1 This chapter presents a short introduction to the structure of the shipping industry and its legislative framework. The chapter also emphasizes fundamental background information that is of relevance to present-day shipping and emissions as well as for the generation of future emissions scenarios.

SEABORNE TRADE AND CONTRIBUTION TO THE ECONOMY

2.2 Pollutant emissions from shipping are linked to shipping activity, which is driven by the world economy. Understanding this mechanism for seaborne transport and other shipping activities is therefore vital to establishing emissions inventories and trends.

2.3 According to UNCTAD [2], about 80% of world trade by volume is carried by sea where demand for seaborne transport is closely linked to the development of the economy. The activity of the shipping industry is expressed in tonne-miles, which is the amount of cargo shipped multiplied by the average distance that it is transported. The volumes of various categories of cargo are shown in figure 2.1, which is based on data from Fearnleys, as printed in the ISL *Shipping Statistics Yearbook 2007* [1]. More detailed information reports on trade and shipping are published annually by UNCTAD [2].

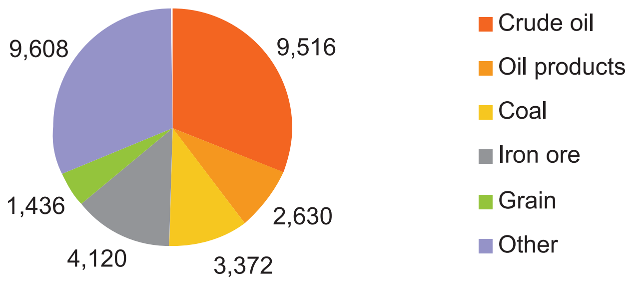


Figure 2.1 *World seaborne trade in 2006 (billion ton-miles)*

2.4 Seaborne transport services the global demand for food, energy, raw materials and finished products. Ships carry essential food such as grains, rice, maize, meat, fish, sugar, and vegetables, vegetable oils, etc., as well as fertilizers to produce more and better crops. Energy, in the form of crude oil, refined petroleum products, coal and gas, is responsible for a significant share of the tonne-miles transported. Furthermore, raw materials such as iron ore, minerals, lumber, scrap iron, cotton, wool, rubber and more are transported, as are semi-finished and finished products. Apart from trade and transportation, various other tasks are performed by special ships. These include offshore service activities, infrastructure development (such as cable laying, pipe laying and dredging), fishing, exploration and research, towing services, etc.

2.5 Seaborne trade has grown with the world economy. Average annual growth rates in tonne-miles for the twenty-year period 1986–2006 are shown in Figure 2.2 and total seaborne trade, expressed in billion tonne-miles, is shown in Figure 2.3. These data were originally generated by Fearnleys by tracking a subset of the world cargo fleet, using ship movement data from Lloyd's Marine Intelligence Unit and data on specific cargoes carried. These data are published, *inter alia*, in the ISL *Statistics Yearbook Shipping 2007* [1].

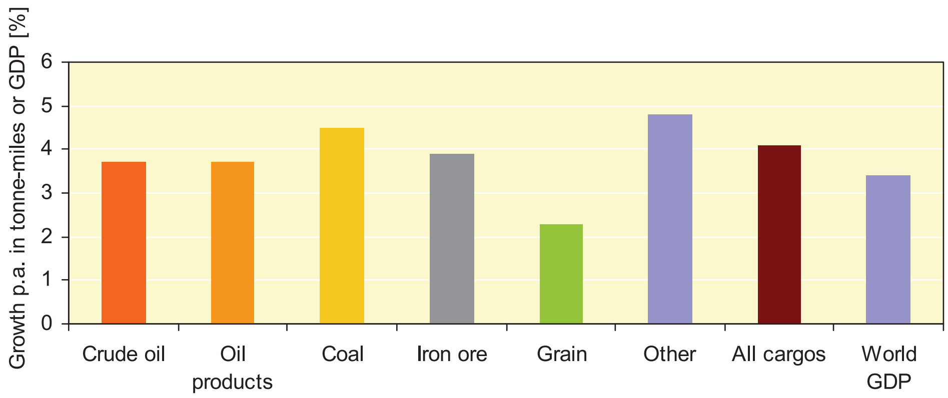


Figure 2.2 *Average annual growth in world seaborne transport and world GDP between 1986 and 2006 [Fearnleys]*

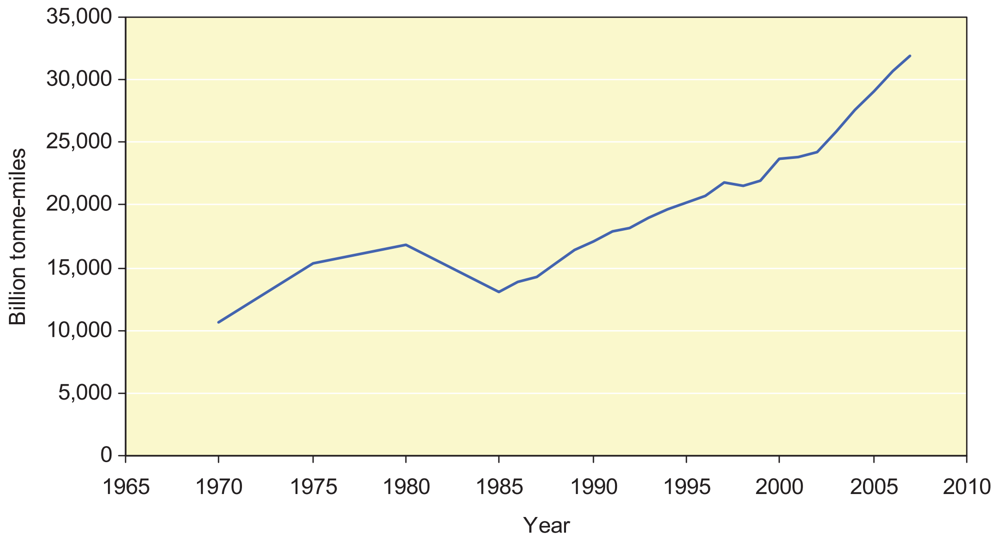


Figure 2.3 *World seaborne trade 1970–2007 in billion tonne-miles [Fearnleys]*

2.6 The overall average annual growth in tonne-miles has been 4.1%. Coal and "other" cargoes have displayed the highest rates of growth (4.5% and 4.8% respectively), while grain has had the smallest annual growth rate (2.3%). In the same period, world economic growth, expressed as real GDP, rose by 3.4% each year on average [3].

2.7 Due to its close connection to trade, international shipping also plays a vital role in facilitation of trade as the most cost-effective means of transport. With economic growth, this shipping industry expanded gradually, and total turnover of marine activities is estimated to be roughly US$ 1.3 trillion in 2004 (Stopford [4]) with an 8% increase compared to 1999, as can be seen in Table 2.1. About one third is related to merchant shipping. The table also demonstrates the growth of the contribution of merchant shipping (22%) over the timeframe.

2.8 Today, the industry employs about 1.23 million seafarers and about half of the total fleet are cargo-carrying ships, operating in over 3,000 major ports [4]. Largest supporting industries for the shipping industry are the shipbuilding and marine equipment industry, with a turnover of US$ 46.9 billion and US$ 90.6 billion respectively in 2004 [4]. The total contribution of marine and shipping activities to world GDP, based on GDP figures from the World Bank [5], can be calculated to be roughly 3% and 1% respectively.

2.9 Other studies value the world marine market at US$ 2.7 trillion [6], with the shipbuilding industry as the largest global market value. The United Nations Conference on Trade and Development (UNCTAD, 2006) [2] estimates an economic contribution to the global economy of US$ 380 billion in freight rates deriving from the operation of ships.

Table 2.1 *Contribution of marine and shipping activities to the economy*

	US$ millions		Growth 1999–2004 (% pa)	Share in 2004 (%)
	1999	**2004**		
1a. Merchant shipping	160,598	426,297	22	31
1b. Naval shipping	150,000	173,891	3	13
1c. Cruise industry	8,255	14,925	12	1
1d. Ports	26,985	31,115	3	2
Total operations	**345,838**	**646,229**	**13**	**47**
2. Shipbuilding	133,170	173,482	5	13
3. Marine resources	95,278	116,933	4	8
4. Marine fisheries	185,817	206,103	2	15
5. Other	179,466	243,898	6	18
Total – US$ millions	939,570	1,386,645	8	100
World GDP (current US$)	31,025,816	41,732,430		
GDP contribution – marine	**3.03%**	**3.32%**		
GDP contribution – shipping	**1.01%**	**1.11%**		

Source: based on Stopford (2009) [4] and figures from the World Bank [5]

2.10 The year-on-year changes in world seaborne trade shown in Figure 2.3 have been used in this study to backcast and forecast emissions where necessary. For instance, emissions from 1990 to 2007 have been estimated from the 2007 inventory, assuming that emissions have grown in proportion with world seaborne trade.

GEOGRAPHICAL DISTRIBUTION OF SHIP TRAFFIC

2.11 The geographical distribution of ship traffic has been investigated in the literature, based on the International Comprehensive Ocean–Atmosphere Data Set (ICOADS), and the Automated Mutual-assistance Vessel Rescue system (AMVER) dataset. ICOADS is a dataset of voluntarily reported ocean and atmospheric observations with ship locations, which is freely available. AMVER is a computer-based and voluntary global ship reporting system, sponsored by the United States Coast Guard but used worldwide by search and rescue authorities to arrange for assistance to persons in distress at sea. While each of these datasets can demonstrate biases, they clearly demonstrate that ship traffic is most prominent in the northern hemisphere and along coastlines. A representation, based on ICOADS data, is shown in Figure 2.4.

2.12 A combined dataset of ICOADS and AMVER data of a total of 1,990,000 daily ship observations at a $1° \times 1°$ spatial resolution has been produced [7]. These data provide the following indication of ship traffic with respect to distance from shore:

- within 200 nautical miles from shore: 70%;
- within 50 nautical miles from shore: 44%; and
- within 25 nautical miles from shore: 36%.

THE WORLD FLEET

2.13 Some key figures regarding the world fleet, based on the Lloyd's Register – Fairplay (LRF) database, are shown in figure 2.5. Due to its link with the mandatory IMO registration, LRF's database can be relied upon to contain virtually all ships engaged in international trade and also many ships that are not. When the IMO ship identification number scheme was introduced in 1987, through the adoption of resolution A.600(15), Lloyd's Register was chosen by IMO to maintain the register on behalf of IMO. The

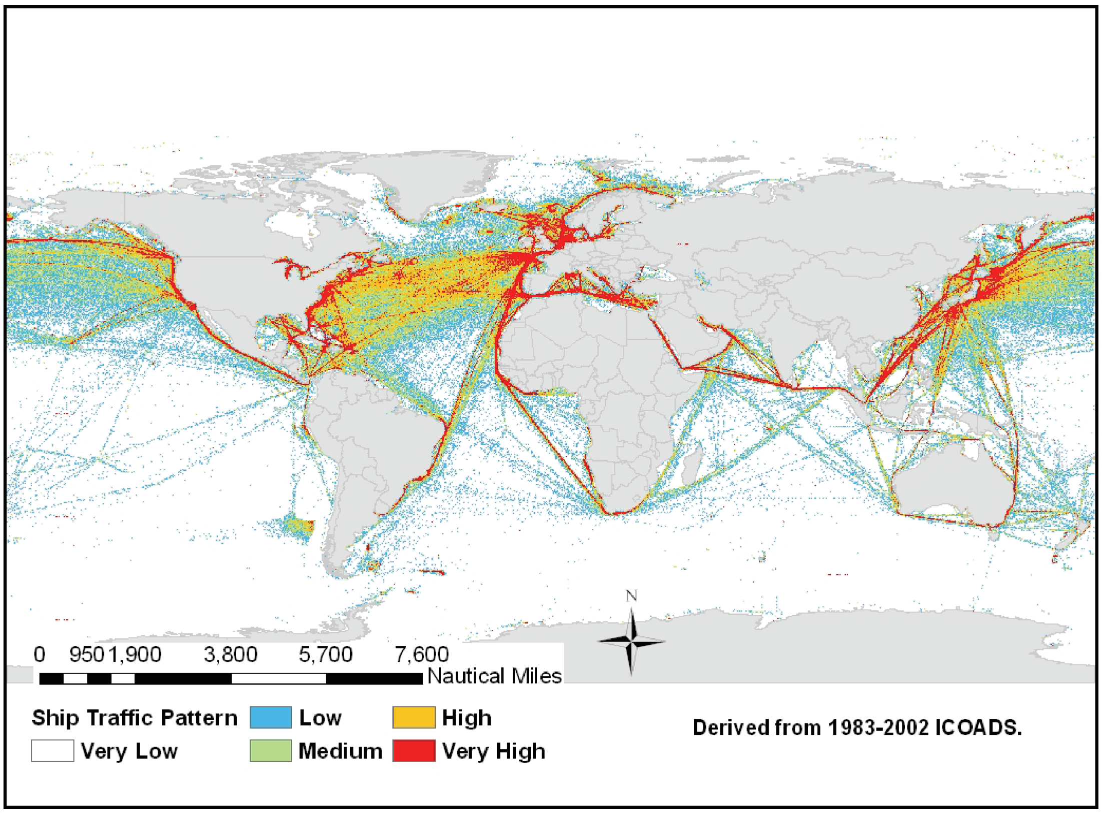


Figure 2.4 *Approximation of ship traffic distribution, based on ICOADS data*

IMO numbering scheme ensures that a permanent number is assigned to each ship for identification purposes. That number remains unchanged upon transfer of the ship to other flag(s) and is inserted in the ship's certificates. The IMO number became mandatory for all ships (with certain limitations) as of 1 January 1996.

2.14 As shown in Figure 2.5, the world fleet in 2007 comprised more than 100,000 ships of more than 100 GT, of which just less than half are cargo ships. However, cargo ships account for 89% of total gross tonnage, clearly indicating the relatively large size of cargo ships.

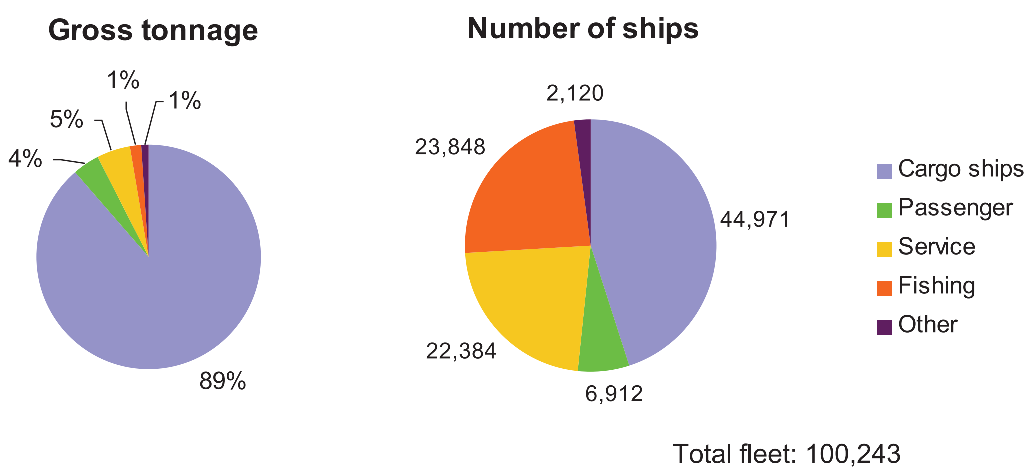


Figure 2.5 *Composition of the world fleet [Lloyd's Register – Fairplay, 2007]*

2.15 A comparison of typical sizes of major cargo ship categories is shown in Figure 2.6 and the respective fleet growth per million dwt for major ship types is given in Figure 2.7. Figure 2.8 visualizes the growth in numbers of the total fleet above 100 GT for the time period 1960 to 2007, based on various publications from Lloyd's Register – Fairplay [8]. The graphs clearly demonstrate the growth in world fleet of merchant vessels in numbers and ship sizes over the years.

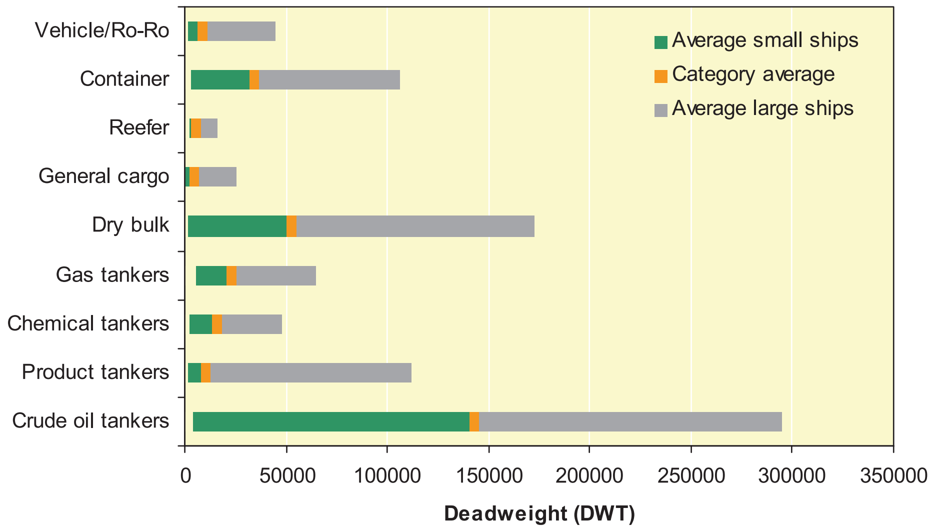


Figure 2.6 *Deadweight of major cargo ship types. High and low end represent average deadweight of the upper and lower ship size categories that were used in the study, not of individual ships, which may be significantly larger or smaller [Lloyd's Register – Fairplay, 2007]*

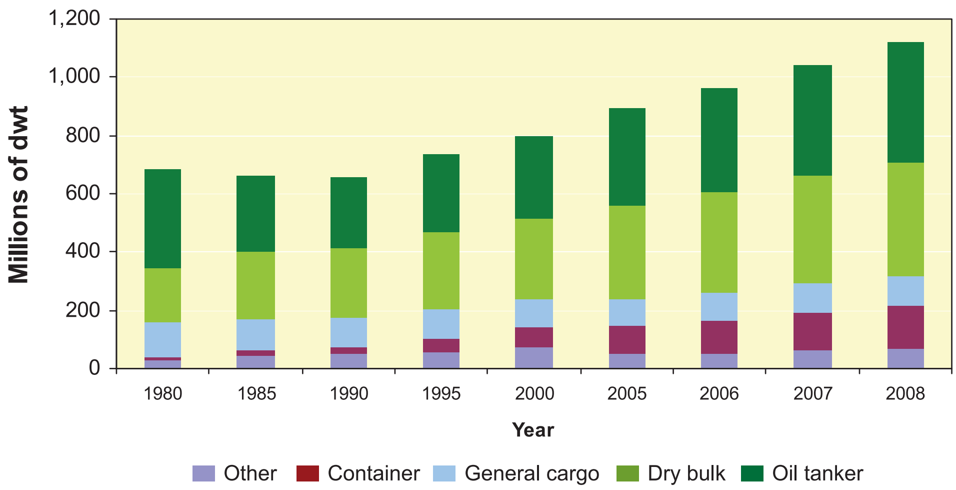


Figure 2.7 *Fleet growth in millions of dwt per major ship type, 1980 to 2008 [UNCTAD, 2008]*

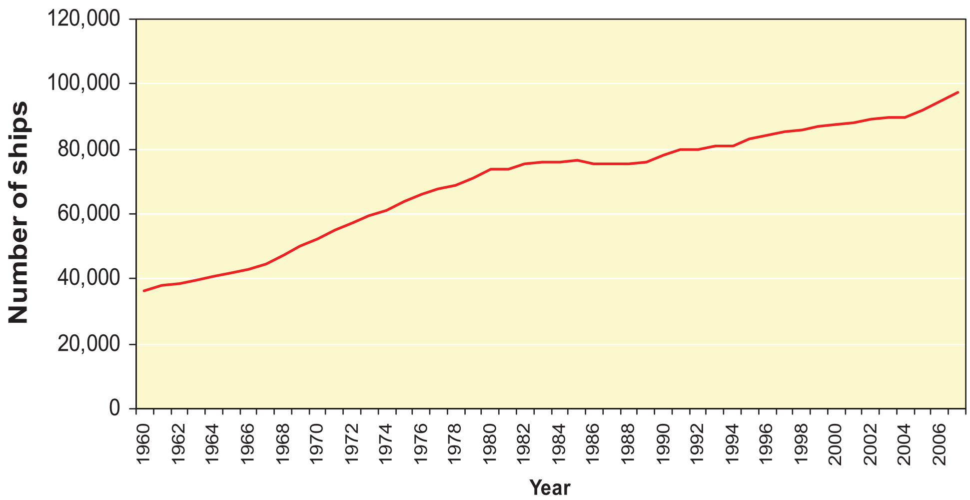


Figure 2.8 *Fleet growth, in numbers of ships, 1960 to 2007 [Lloyd's Register – Fairplay]*

2.16 Ships are characterized by the type of cargo they are designed to carry. Table 2.2 lists the definitions of primary ship categories that have been used in the emissions inventory for this study. More detailed description of the various ship types can be found in general literature such as [9] and [10] and other reference resources, such as on the internet [13 and 14]. Ships that are constructed to carry refrigerated or frozen cargo are commonly referred to as "reefer ships".

Table 2.2 *Definitions of the ship categories that have been used in the emissions inventory for this study*

Cargo ships	**Crude carriers** include tankers which are intended for carrying crude oil.
	Products tankers carry various types of refined petroleum products.
	Chemical tankers carry various types of industrial chemicals.
	LPG tankers are specialized tankers for the carriage of Liquefied Petroleum Gas and often also other products, for example ammonia.
	LNG tankers are specialized tankers for the carriage of Liquefied Natural Gas.
	Other tankers include a large number of bunker tankers and also those that carry a wide range of liquid niche products such as orange juice, bitumen, wine and water.
	Bulk carriers are ships designed to carry bulk goods such as grain, iron ore, coal and more.
	General cargo carriers include a wide variety of cargo ships from small one-hold vessels to highly advanced Multi-Purpose Vessels. Some of the ships are designed to carry containers as well as break-bulk cargoes. Many of these ships are equipped with their own lifting gear.
	Other dry carriers are carriers of refrigerated cargo and other special dry cargo ships.
	Container ships are built to carry containerized cargo and nothing else, i.e. fully cellular ships designed to carry containers both on deck and under deck.
	Vehicle ships are designed to carry (new) cars, trucks and sometimes other special cargo on wheels.
	Ro-Ro are ships that are loaded and discharged by driving the cargo on board on wheels.
Other	**Ferries** carry cars and passengers on regular schedules. This also includes overnight ferries.
	Cruise ships carry passengers on pleasure voyages.
	Yachts are large pleasure vessels.
	Offshore This category encompasses a wide range of platform supply vessels and offshore support vessels. Drilling rigs are not included in this figure.
	Service These are mainly tugs but also work-boats, dredgers, research vessels and more.
	Fishing vessels are designed to capture fish.

2.17 The age profile of the world fleet, also from Lloyd's Register – Fairplay, is shown in Figure 2.9, where it can be observed that, by number of vessels, approximately half of the world fleet is more than 20 years old (constructed before 1987). When gross tonnage, rather than number of ships, is considered (see Figure 2.10), we can see that ships older than 20 years amount only to 25% of the total gross tonnage. In

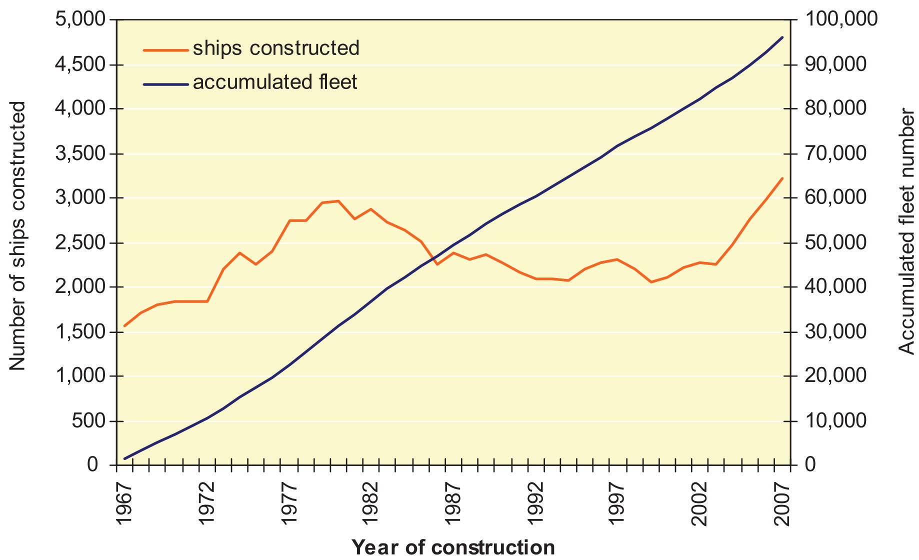


Figure 2.9 *Age profile of the world fleet [Lloyd's Register – Fairplay, 2007]*

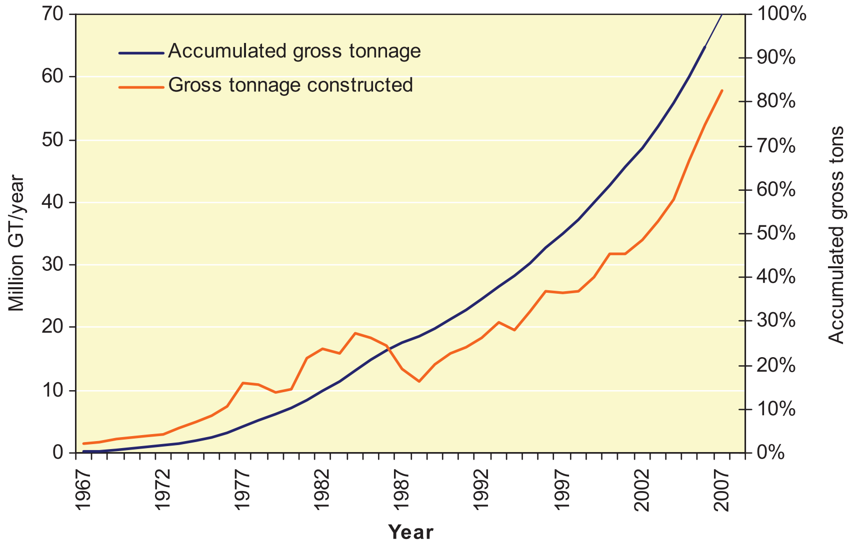


Figure 2.10 *Age profile of the world fleet by gross tonnage [Lloyd's Register – Fairplay, 2007]*

terms of gross tonnage, about half of the fleet is 10 years old or less. Combined, these figures show that a large number of smaller vessels of some age are in service. These ships represent a smaller share of the total transport capacity.

2.18 A comparison of the deadweight tonnage of the current fleet and the order book for dry and wet bulk (tankers and dry bulk carriers) is shown in Figure 2.11. Due in part to the current global financial situation in 2009, there is reason to believe that a significant number of these ships may not be built.

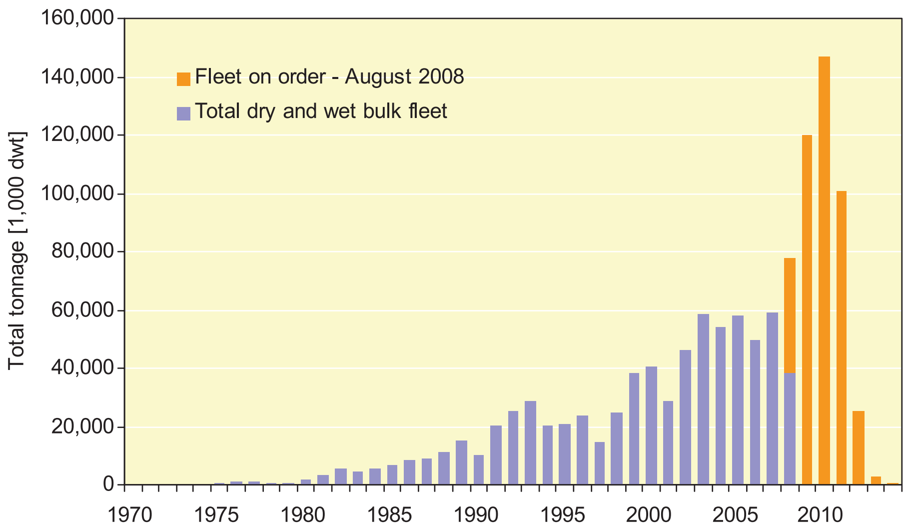


Figure 2.11 *Dry and wet bulk fleet and order books [Fearnleys, August 2008, and Lloyd's Register – Fairplay]*

FLAG AND OWNERSHIP STRUCTURES OF THE WORLD FLEET

2.19 The structures and mechanisms which govern the shipping industry are complex, due to its international nature. While all ships are uniquely registered in a national register, it is not always easy to identify the "country of domicile" of ships' controlling interests since there are many types of ownership structures in shipping. For instance, stockholding companies may be owned by a large number of nationals from different countries. A company may be holding shares of less than 100 per cent in companies in third countries, etc. In spite of these difficulties, statistics on "country of domicile" of ships' controlling interests are presented by UNCTAD [2]. Some key facts and figures are shown here and are also brought into relation to trading volumes.

2.20 The top ten ship registries by deadweight are shown in Table 2.3. In addition, the number of ships, the share of deadweight to total deadweight and their growth are given. Together, these registers control about 69% of the global total deadweight tonnage.

Table 2.3 *Top ten ship registers [UNCTAD, 2008]*

Flag of registration	Number of ships	Total tonnage (1,000 DWT)	Share of world total DWT (%)	% dwt growth 2007/08
Panama	7,616	252,564	22.6	8.8
Liberia	2,173	117,519	10.5	11.7
Greece	1,477	61,384	5.5	11.3
Bahamas	1,422	59,744	5.3	8.2
Marshall Islands	1,097	59,600	5.3	9.1
Hong Kong, China	1,238	59,210	5.3	9.0
Singapore	2,243	55,550	5.0	8.8
Malta	1,442	45,218	4.1	12.5
China	3,816	37,124	3.3	6.3
Cyprus	982	29,431	2.6	–0.7

2.21 For many years there has been a trend towards more and more ships being registered under a foreign flag. UNCTAD [2] indicates that the percentage of foreign-flagged vessels grew from 41.50% in 1989 to 66.35% in 2007. However, a very marginal decrease from 2006 to 2007 is a signal that a saturation point may have been reached. If second registries, such as the NIS (Norwegian Shipping Register), as well as ships registered under the flag of the Netherlands Antilles for the Netherlands are included, the share of "foreign-flagged" vessels becomes more than 71% of the world fleet's deadweight tonnage [2].

2.22 Table 2.4 presents the top ten controlling nations[1] as of January 2008. In terms of deadweight tonnage, these nations control 70.2% of the world fleet. Percentage changes from 2007 to 2008 and the share of deadweight tonnage under national registry, as of 2008, are also presented.

Table 2.4 *Top ten controlling interests by domicile [UNCTAD, 2008]*

Controlling interest's country of domicile	Number of ships	Total tonnage (1,000 dwt)	Share of world total dwt (%)	% Dwt growth 2007/2008	% Share of dwt in national registry
Greece	3,115	174,570	16.8	–0.6	31.9
Japan	3,515	161,747	15.6	0.5	7.2
Germany	3,208	94,222	9.1	0.4	15.5
China	3,303	84,881	8.2	1.0	40.5
Norway	1,827	46,872	4.5	–0.5	30.3
United States	1,769	39,828	3.8	–1.1	51.0
Republic of Korea	1,140	37,703	3.6	0.3	50.7
Hong Kong, China	657	33,424	3.2	–1.4	54.5
Singapore	869	28,632	2.8	0.1	57.4
Denmark	861	27,434	2.6	0.4	38.2

1 According to UNCTAD and based on the definition of Lloyd's Register – Fairplay, the controlling nation is represented by the country of ownership with the true controlling interest. Sometimes this is not straightforward to distinguish in shipping.

2.23 In order to provide an overview of the international nature of shipping, Table 2.5 presents the top 15 trading nations and presents their respective fleet and ownership profiles. One can easily see that the top 15 trading nations account for 65% of the world trade in terms of value and their owning interest lies in 54% of the world fleet in terms of deadweight. However, their corresponding share in registration lies only by 19% of the world fleet in terms of deadweight.

Table 2.5 *Top fifteen trading nations, with respective fleet and ownership profiles [UNCTAD, 2008]; trade data are for 2007, fleet data are for 2008*

Top trading nations	% share of world trade in terms of value	% of world fleet in terms of dwt	% of ownership of fleet in terms of dwt
United States of America	11.38	1.09	3.84
Germany	8.51	1.34	9.07
China	7.81	3.32	8.18
Japan	4.77	1.32	15.58
France	4.16	0.71	0.63
United Kingdom	3.76	0.42	2.5
Netherlands	3.72	0.56	0.83
Italy	3.55	1.19	1.71
Belgium	3.01	0.58	1.17
Canada	2.88	0.28	1.81
Republic of Korea	2.62	1.89	3.63
Hong Kong, China	2.56	5.3	3.22
Spain	2.18	0.25	0.43
Russian Federation	2.16	0.64	1.74
Mexico	2.04	0.14	n/a
Total – top 15	**65.11**	**19.03**	**54.34**
Total – top 25	**78.02**	**28.16**	**64.93**

2.24 Furthermore, in comparing Table 2.5 with Tables 2.4 and 2.3, one can observe that the biggest registries, such as Panama, Liberia and the Bahamas, do not appear in the top controlling nations nor in the top trading nations. An exception is Greece with respect to controlling interest, where 31.9% of the tonnage under Greek-controlled interests is also carrying the national flag. In general, the motivation for a vessel owner to use a foreign flag may include more favourable tax regimes, conditions to finance ships and the possibility of employing foreign seafarers. These are all common practices in shipping, and underline the international structure of the shipping industry.

REGULATION OF SHIPPING

2.25 Marine activities such as international shipping are regulated by a mixture of the international law of the sea and the law of a particular State. *The United Nations Convention on the Law of the Sea* (UNCLOS) is the cornerstone of international maritime law. UNCLOS endorses the right of any sovereign State to have a ship register and thus become a flag State, and it provides ships with the right to innocent passage through territorial waters and economic zones. International law, such as UNCLOS, regulates the affairs between States but does not apply directly to individual ships [10].

2.26 Ships are regulated by applicable laws and regulations of the country in which the ship is registered, i.e. the flag State. Some countries may require specific criteria to be fulfilled before granting a ship access to the registry. Such criteria could be that the ship is built in their territory, that the shipowning company is registered in the country, that the owners are citizens of the country and more. Other countries have few or no restrictions on access, and are commonly referred to as “open registries”. If the ship is to engage in international shipping, i.e. entering foreign or international waters, the flag State is obliged to ensure that the ship complies with regulations set down in international conventions and agreements to which the flag State is party.

2.27 Regional and national regulations can be applied within areas of jurisdiction by coastal States. Generally, such national regulations define legal boundaries for the operation of the ships, since the provisions for innocent passage that are defined by UNCLOS mean that such laws and regulations shall not apply to the design, construction, manning or equipment of foreign ships unless they are giving effect to generally accepted international rules or standards.

2.28 Figure 2.12 provides an overview of the various players in the industry in shipping and presents their respective roles with respect to enforcing the legislative framework. The legislative framework for international shipping today consists of 50 conventions and protocols created by the International Maritime Organization (IMO), of which 41 are in force, and relevant legislative measures of the International Labour Organization (ILO) for seafarers. It is the Contracting Government's responsibility to transpose international law into their national legislation and enforce it. The right-hand side of Figure 2.12 presents the various other industry interests around the shipowner, such as banks who finance ships, insurance companies who insure ships and companies who are involved in the commercial and day-to-day operation of a vessel (ship operator, manager).

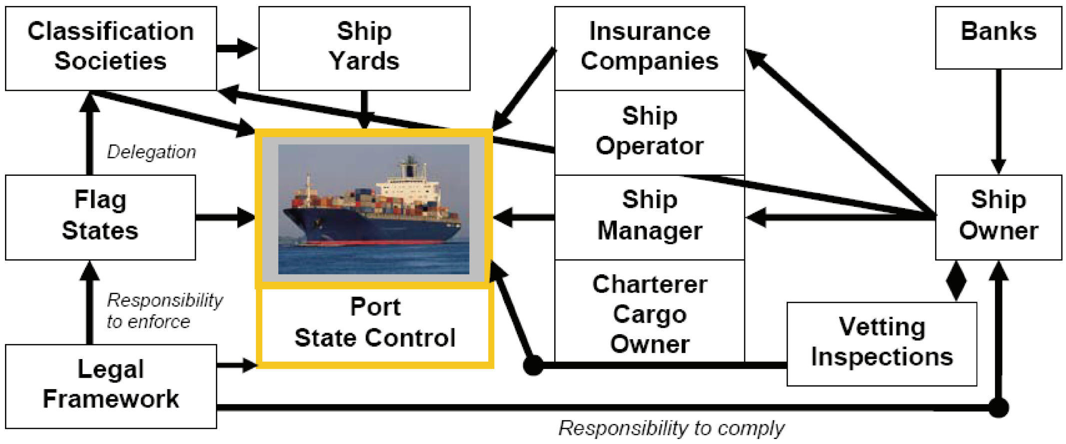


Figure 2.12 *Players of the legislative framework for shipping [15]*

2.29 The International Maritime Organization has been established "to provide machinery for cooperation among Governments in the field of governmental regulation and practices relating to technical matters of all kinds affecting shipping engaged in international trade; to encourage and facilitate the general adoption of the highest practicable standards in matters concerning maritime safety, efficiency of navigation and prevention and control of marine pollution from ships." [11]. The Organization is also empowered to deal with administrative and legal matters related to these purposes.

2.30 IMO's role is thus primarily to adopt legislation, while enforcement lies with the Contracting Governments (the flag States). Governments decide whether or not to ratify legislation negotiated by IMO Member States. When a Government ratifies an IMO convention, the Government effectively agrees to make the regulation part of its own national law and sometimes delegates survey activities to classification societies, which then act on behalf of the flag State. Classification societies are companies who deal with the technical aspect of shipping and sometimes also conduct surveys on behalf of the flag State. In this case, they are often called a "recognized organization" (RO).[2] Classification societies also play an important role for the construction of vessels, since ships are normally constructed according to classification rules.

2.31 Each convention includes appropriate provisions stipulating conditions which have to be met before it enters into force. Typically, entry into force is conditional on a certain number of countries, representing a certain share of the world fleet gross tonnage, ratifying the agreement. When an IMO instrument has entered into force, it is considered to be generally accepted as international rules or standards, and

2 See IMO resolutions A.739(18) "Guidelines for the authorization of organizations acting on behalf of the Administration", and its amendment in MSC.208(81), and A.789(19) "Specifications on the survey and certification functions of recognized organizations acting on behalf of the Administration".

UNCLOS no longer prohibits rules applying to the design, construction, manning or equipment of foreign ships in innocent passage [12].

2.32 When an IMO instrument has entered into force, countries that have ratified the instrument can apply it not only to ships of their own flag but to all ships, regardless of flag. Therefore, ships wanting to enter the ports or waters under the jurisdiction of a county that has ratified an IMO instrument will have to abide by that convention, regardless of flag. This is an important principle, commonly referred to as the principle of "no more favourable treatment". It refers to port States enforcing applicable standards in a uniform manner to all ships in their ports, regardless of flag.

2.33 Due to this principle and the international nature of shipping, an IMO regulation affects, *de facto*, most ships, regardless of flag, once it has entered into force. On the other hand, there are no legal barriers to prevent a ship from not conforming to a given IMO regulation provided it operates solely outside the area of jurisdiction of countries that have ratified the convention in question.

2.34 Flag States are responsible for implementing and enforcing legislation on ships in their registries. Additionally, many of IMO's most important technical conventions contain provisions to allow ships to be inspected when they visit foreign ports, to ensure that they meet IMO requirements. This is referred to as "Port State Control" (PSC). Ships that fail to meet the standards when subjected to PSC can be detained until repairs are carried out and the ship is released from detention. In order to ensure a harmonized and coordinated approach for PSC inspections, many countries have organized themselves into groups, based on memoranda of understanding (MoUs), and are therefore grouped in regional PSC regimes. There are currently nine such port State control regimes, covering most coastal States, as follows:

1. Europe and North Atlantic (Paris MoU), signed in 1982;
2. Asia and the Pacific (Tokyo MoU), signed in 1993;
3. Latin America (Acuerdo de Viña del Mar), signed in 1992;
4. Caribbean (Caribbean MoU), signed in 1996;
5. West and Central Africa (Abuja MoU), signed in 1999;
6. Black Sea (Black Sea MoU), signed in 2000;
7. Mediterranean (Mediterranean MoU), signed in 1997;
8. Indian Ocean (Indian Ocean MoU), signed in 1998; and
9. Arab States of the Gulf (Riyadh MoU), signed in 2004.

2.35 In addition, the United States Coast Guard (USCG) has also established a foreign vessel inspection service which is not part of any of the MoUs but which follows any of the developments and harmonization efforts of the other PSC regimes.

2.36 In addition to inspections carried out by port State control officers, the industry also carries out vetting inspections, primarily for tankers and dry bulk carriers. These vetting inspections are driven by cargo interests or shipowners, depending on the scheme.

UNFCC, THE KYOTO PROTOCOL AND SHIPPING

2.37 The United Nations Framework Convention on Climate Change (UNFCCC) was signed in 1992, entered into force in 1994, and in March 2009 had 192 Parties [16]. Under the Convention, parties gather and share data, launch national strategies to address emissions and cooperate for the adaptation to climate change. In December 1997, the Kyoto Protocol was adopted and entered into force in February 2005; in March 2009, 184 parties [16] had ratified the Protocol.

2.38 While the Convention does not provide commitments to stabilize emissions, the Protocol sets binding targets for the Annex I countries. These countries agreed to reduce their overall emissions of six greenhouse gases by an average of 5.2% below 1990 levels between 2008 and 2012. In doing so, the Kyoto Protocol offers several mechanisms to reduce emissions, as follows: (1) emissions trading, (2) the clean development mechanism (CDM) and (3) the joint implementation (JI) mechanism. Joint implementation allows a country to earn emission-reduction units (ERUs) from either an emission-reduction or an emission-removal project while the CDM allows a developed country to earn saleable certified emission reductions (CER) for emission-reduction projects in developing countries.

2.39 While emissions from aviation and maritime transport have been part of the UNFCCC agenda, these emissions were not included under the Kyoto Protocol. Article 2.2 of the Kyoto Protocol reads [16]:

> "The Parties included in Annex I shall pursue limitation or reduction of emissions of greenhouse gases not controlled by the Montreal Protocol from aviation and marine bunker fuels, working through the International Civil Aviation Organization and the International Maritime Organization, respectively."

2.40 A topic of debate within IMO is how the wording of Article 2.2 of the Kyoto Protocol should be interpreted and if the principle agreed under UNFCCC of "common but differentiated responsibility" should apply to a GHG regime for international shipping rather than IMO's basic principle of "no more favourable treatment" explained earlier.

2.41 For clarification purposes, the principle of "common but differentiated responsibility" recognizes the differences in the contributions of developed and developing countries in addressing global environmental issues, such as addressing the emissions of greenhouse gases. The principle is enshrined in Article 3.1 of the UNFCC Convention [16] as follows:

> "The Parties should protect the climate system for the benefit of present and future generations of humankind, on the basis of equity and in accordance with their common but differentiated responsibilities and respective capabilities. Accordingly, the developed country Parties should take the lead in combating climate change and the adverse effects thereof."

2.42 Following the discussions at IMO [17], a number of countries maintained the view that any measures to reduce emissions of GHGs to be adopted by IMO should only be applicable to Annex I parties to the UNFCCC and its Kyoto Protocol, in accordance with the principle of "common but differentiated responsibility". Some delegations therefore have the view that reduction of emissions related to international shipping should be on a voluntary basis for developing countries.

2.43 As the legal advice from IMO's Sub-Division for Legal Affairs in document MEPC 58/4/20 clearly indicates, there is no potential treaty law conflict between the Kyoto Protocol and the provisions that may be developed by the Organization on control of GHG emissions from international shipping.

2.44 Other delegations have expressed the opinion that, given the global mandate of IMO as regards safety of ships and the protection of the marine and atmospheric environment from all sources of ship pollution, the IMO regulatory framework on GHG emissions should be applicable to all ships, irrespective of the flags they fly.

2.45 As demonstrated earlier, the ownership and management chain surrounding ship operations can involve many players, located in various countries. In addition, the registration of a ship can move between jurisdictions several times over its lifetime. It is worth noticing that about three quarters of the world tonnage, by deadweight, of all merchant vessels engaged in international trade is registered in developing countries (not in Annex I of the Kyoto Protocol), hence making it a large portion of the world fleet; it would be ineffective for any regulatory regime to act only on the remaining portion, namely one quarter of the world fleet.

2.46 Given IMO's global mandate, given by the IMO Convention itself as well as from UNCLOS, there is no precedence in any of the more than fifty IMO treaty instruments currently in existence where measures are applied selectively to ships according to their flag. On the other hand, there are several international environmental agreements which have a differentiated approach, such as the Montreal Protocol (on substances that deplete the ozone layer), yet, when IMO has dealt with the same issues, the principle of differentiated approach has not been taken on board.

REFERENCES

1 *Shipping Statistics Yearbook 2007*. Institute of Shipping Economics and Logistics (ISL), Bremen, Germany. ISSN 0721–3220.

2 Review of Maritime Transport, United Nations Conference on Trade and Development (UNCTAD), 2006, 2007, 2008.

3 International Monetary Fund IMF, 2007 http://www.imf.org/external/pubs/ft/weo/2008/01/index.htm#ch1fig
4 Stopford, M. 2009. *Maritime Economics*, 3rd edition, Routledge, London.
5 World Bank, Key Development Indicators http://web.worldbank.org/WBSITE/EXTERNAL/DATASTATISTICS/0,,contentMDK:20535285~menuPK:1390200~pagePK:64133150~piPK:64133175~theSitePK:239419,00.html
6 South East of England Development Agency (SEEDA) http://www.seavisionuk.org/news.cfm?widCall1=customWidgets.contentItem_show_1&cit_id=4409
7 Dalsøren, S.B., Eide, M.S., Endresen, Ø., Mjelde, A., Gravir, G. and Isaksen, I.S.A. 2009. "Update on emissions and environmental impacts from the international fleet of ships. The contribution from major ship types and ports". *Atmospheric Chemistry and Physics*, 9: 2171–2194. http://www.atmos-chem-phys.net/9/2171/2009/acp-9-2171-2009.pdf
8 Lloyd's Register – Fairplay, World Fleet Statistics, various publications.
9 Wijnholst, N., and Wergeland, T. 2009. *Shipping Innovation*, IOS Press. ISBN 978-1-58603-943-1.
10 Morgan, N. (ed.). 1990. *Marine Technology Reference Book*, Butterworth & Co Publishers. ISBN 0-408-02784-3 (978-0-408-02784-7).
11 IMO Convention, article 1(a). This is on the webpage http://www.imo.org
12 United Nations Convention on the Law of the Sea of 10 December 1982 http://www.un.org/Depts/los/convention_agreements/texts/unclos/UNCLOS-TOC.htm
13 Wikipedia "Commercial Vessels" http://en.wikipedia.org/wiki/Commercial_vessel
14 Wikipedia "Merchant Vessel" http://en.wikipedia.org/wiki/Merchant_ship
15 Knapp, S., and Franses, P.H., "Comprehensive Review of the Maritime Safety Regimes – Present status and recommendations on improvement" Econometric Institute Working Paper 2007–19, Erasmus University Rotterdam, The Netherlands.
16 United Nations Convention Framework on Climate Change http://unfccc.int/essential_background/convention/items/2627.php
17 IMO, Main events in IMO's work on limitation and reduction of greenhouse gas emissions from international shipping, Note from the IMO Secretariat, London, November 2008

3

Emissions from shipping 1990–2007

OVERVIEW OF METHODOLOGY FOR QUANTIFICATION OF EMISSIONS

3.1 This study provides estimates of present emissions from international shipping. "International shipping" has been defined in accordance with the IPCC Guidelines, i.e. shipping between ports of different countries irrespective of vessel's flag. International shipping excludes military and fishing vessels. By this definition, the same ship may frequently be engaged in both international and domestic shipping. Total estimates that include emissions from domestic shipping and from fishing are also included in this report. Emissions from naval activities are not included.

3.2 The study addresses greenhouse gases considered under the UNFCCC process (CO_2, CH_4, N_2O, HFCs, PFCs, SF_6) and other relevant substances, as defined in the terms of reference (NO_x, NMVOC, CO, PM, SO_x). Emissions from ships can be categorized as:

- Emissions of exhaust gases;
- Cargo emissions;
- Emissions of refrigerants; and
- Other emissions.

3.3 Exhaust-gas emissions covered in this study are emissions from main engines, auxiliary engines and boilers. Exhaust from incinerators is regarded as a very small contributor and is not included. Refrigerants are mainly used for refrigeration/freezers of cargo and provisions and in air-conditioners. Refrigerants are emitted to the atmosphere through leaks that occur during the operation and during the maintenance of refrigerating and air-conditioning equipment. Refrigerant gas may also be released in the course of scrapping. Emissions of refrigerants from scrapping are generally allocated to the country in which the ship was scrapped. Other emissions arising from scrapping are not included in this report. Cargo emissions include various emissions and leakages, including leaks of refrigerant from refrigerated containers and trucks, release of volatile compounds (CH_4 and NMVOCs) from liquid cargoes, etc. Other emissions arise from diverse sources, including emissions from testing and maintenance of fire-fighting equipment. These are not considered to be significant and are not further discussed here.

3.4 This study includes detailed calculations of emissions of exhaust gases. Cargo emissions, refrigerant emissions and other emissions have been assessed on the basis of data obtained from previous studies.

3.5 GHG and pollutant emissions in exhaust gases have been estimated by establishing fuel-based emission factors for each of the relevant components of the exhaust gas and a fuel consumption inventory. Fuel-based emission factors are values for conversion from consumed fuel to the emissions that are derived from a combustion process. The emissions are subsequently estimated by multiplying the fuel consumption by the emission factors.

3.6 In order to perform the basic emissions inventory in line with recognized standards, the default emission factors prepared by IPCC and by the UNECE/EMEP CORINAIR programme are used, with the exception of NO_x, where more detail is needed to account for the NO_x emission standard that was introduced with regulation 13 of MARPOL Annex VI. In line with the above-mentioned guidelines for creating an inventory of emissions, the following pollutants were considered for exhausts: NO_x, SO_2, PM_{10}, CO, CO_2, N_2O, CH_4, and NMVOC.

3.7 The exhaust emissions inventories presented in this study cover consumption in main engines, auxiliary engines and boilers on board all ships larger than 100 GT. Two inventories are provided:

1. Total emissions, comprising emissions from domestic shipping and fishing; and
2. Emissions from international shipping, excluding fishing and domestic shipping.

3.8 Emissions inventories are established for the year 2007. Emissions for the years from 1990 up to 2007 are estimated by assuming that emissions from shipping are proportional to the estimates of seaborne trade published by Fearnleys (see Figure 2.3 in Chapter 2).

ESTIMATE OF FUEL CONSUMPTION FROM 1990 TO 2007

3.9 Fuel consumption by vessels was estimated for 2007 by means of two methodologies:

1. based on activity data (bottom-up approach); and
2. based on fuel statistics (top-down approach).

3.10 Results are compared and discussed, with the aim of identifying a consensus estimate for fuel consumption in 2007 by international shipping and by shipping as a whole. This chapter summarizes work done on estimating fuel consumption between 1990 and 2007. More details can be found in Appendix 1.

3.11 In the activity-based approach, the fuel consumption is estimated for individual ship categories. The main engine (ME) fuel consumption of a ship category is estimated by multiplying the number of ships in each category with the average ME power to find the installed power (kW) by category. The annual power outtake (kW·h) is then estimated by multiplying the installed power with a category-specific estimate of the operating hours of the main engine and the average engine load factor. Finally, the fuel consumption is estimated by multiplying the power outtake with the specific value of fuel oil consumption that is applicable to the engines of the given category (g/kW·h). The process of estimating the fuel consumption of a ship category is illustrated in Figure 3.1. The same principle is applied to estimate the fuel consumption of the auxiliary engine. Emissions from boilers have been estimated for tanker ships, based on assumptions regarding frequency of carrying heated cargoes, number and length of laden voyages and the consumption of fuel per day to heat the steam boiler.

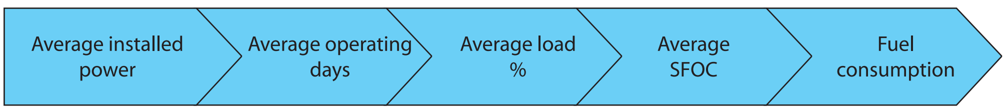


Figure 3.1 *Activity-based calculation of fuel consumption*

3.12 Significant data are needed for this type of assessment, and not all of these data are available for individual ships at this level of analysis. Comments on the confidence and uncertainty of main inputs are shown in Table 3.1 and Table 3.2.

3.13 Fuel statistics have their limitations with respect to coverage, consistency of reporting and accuracy in various parts of the world; this presents a risk of errors and under-reporting in fuel statistics. In general, estimation of fuel consumption entails a significant degree of uncertainty, as evidenced by the differences that have been observed in previous estimates (Corbett and Köhler, 2003 [1]; Eyring *et al.*, 2005 [3]; Endresen *et al.*, 2003, 2007 [5, 6]; Gunner, 2007 [8]; Olivier *et al.*, 2001 [11]; Skjølsvik *et al.*, 2000 [12]; Corbett and Fischbeck, 1997 [15]). Estimates of fuel consumption from statistics as well as estimates in this and previous studies are illustrated in Figure 3.2. Corrections have been applied to enable comparison to be made, as explained in Appendix 1.

3.14 Activity-based estimates consistently predict values of fuel consumption that are higher than what is indicated in fuel statistics. While these activity-based estimates share many common inputs and assumptions, and as such are not fully independent, statistical data, on the other hand, include apparent errors and other inconsistencies that could be expected to cause under-reporting of consumption.

3.15 Following the discussions detailed in Appendix 1 of this report, the international team of scientists conducting this study (named in the preface to this report) concluded that activity-based estimates provide

Table 3.1 *Confidence and uncertainties of calculations of fuel consumption of main engines*

Input	Source	Confidence	Comment
Number of ships, by category	Fairplay database	Very high, well known	High accuracy of registered ships. Uncertainty regarding whether all ships are actively trading or if some ships in some categories are laid up, etc.
Average main engine size	Fairplay database	Very high, well known	High accuracy expected.
Average main engine operating days	Calculated from AIS data except for ship types with low AIS coverage	Moderate, but dominates uncertainty	Accuracy depends on accuracy of AIS collection system, how representative are ships that are moving between ports with AIS network coverage, assumptions made for ship movement, cut-off and filtration of data, assumed average offhire/lay-up, port-to-port distance calculations, vessel design speed.
Average main engine load	Default values were calculated from AIS average speed and Fairplay design speed. Defaults were replaced where other data or special conditions suggested this to be appropriate.	Moderate; secondary influence on uncertainty	Calculations are sensitive to vessel design speed data from the extended Lloyd's database and errors in estimating the AIS at-sea speed. Moreover, engine load will be over-estimated when ship is in ballast or lightly loaded. Where other data suggest that the results are unreasonable, calculated values are substituted by expert judgement.
Average offhire/lay-up	Assumed	Moderate; influences the number of main engine operating days	It is assumed for all ships that the effective calendar is 355 days (on average, 10 days is spent out of active trade).
Calculations of distances between AIS observations	Calculations were based on AIS coordinates	Moderate	Used for AIS calculations of average speed. Accuracy will be affected when there is a land mass within the shortest route between AIS receivers. Where other data suggest that the results are unreasonable, calculated values are substituted by expert judgement.
Vessel design speed	Extended Fairplay database	Moderate	Used to determine cut-off between "normal" and "slow" (abnormal) voyages. Also used to estimate power factor at sea.
Average main engine SFOC	Estimated from a wide range of test-bed and other data	High, well known	While there is some variation from engine to engine, the average figure is expected to have comparatively high accuracy.

a more correct representation of the total emissions from shipping than what is obtained from fuel statistics. Our team agreed that the activity-based estimate (Table 3.3) should be used as the consensus estimate from this study, and prepared estimates of high and low bound, using alternate inputs to quantify the degree of uncertainty. Since the activity-based model cannot separate domestic shipping from international shipping, figures from bunker statistics for emissions from domestic shipping have been used in the calculation of emissions from international shipping. The estimates of upper and lower bounds that were agreed to by the team are about 20% higher and lower than the central consensus estimate; these bounds do not represent the full range of possible calculations under uncertain inputs, but the range that is best supported by the available data. Table 3.4 shows the fuel consumption, divided by fuel type and by combustion source. The ratio between residual and distillate fuel is, in reality, based on fuel statistics, since this ratio was used to calibrate the assumptions of fuel type in the activity-based model. Table 3.5 shows estimates of fuel consumption for the years 1990–2007. These data are calculated by back-casting the 2007 estimate, using Fearnleys' data on seaborne trade.

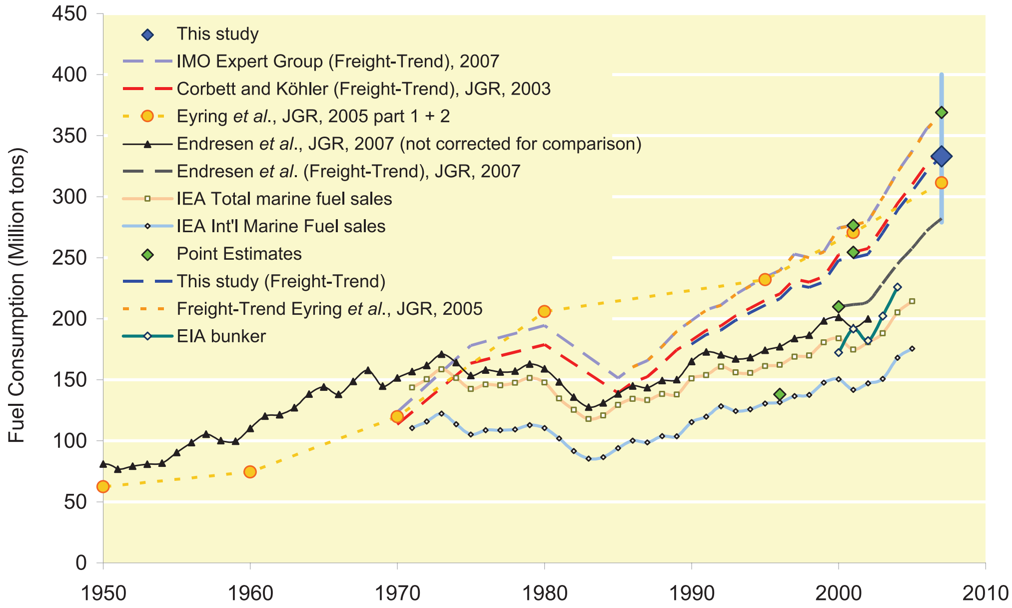


Figure 3.2 *World fleet fuel consumption (except military vessels) from different activity-based estimates and statistics. Symbols indicate the original estimates for individual years and the solid lines show the original estimates of trend. Dashed lines show the backcast and forecast, calculated from the time evolution of freight tonne-miles with the point estimates. The blue square shows the activity-based estimate from this study and the blue range bar indicates the high and low bound estimates*

Table 3.2 *Confidence and uncertainties of calculations of fuel consumption of auxiliary engines*

Input	Source	Confidence	Comment
Number of ships, by category	Fairplay database	Very high, well known	High accuracy of registered ships. Uncertainty regarding whether all ships are actively trading or if some ships in some categories are laid up, etc.
Average auxiliary engine size	Extended Fairplay database	High, but with data gaps	Accuracy somewhat lower than main engine data; however, relatively high accuracy is expected.
Average auxiliary engine operating days	Expert judgement and consultations with operators	Moderate, dependent upon vessel operating days and auxiliary demand	Assessment is challenging due to variability in ship power demands and operating practices. While confidence is moderate, the impact on total inventory is small.
Average auxiliary engine load	Expert judgement and consultations with operators	Moderate, dependent on vessel operating conditions and demand	Assessment is challenging, due to variability in ship power demands and operating practices.
Average auxiliary engine SFOC	Estimated from a wide range of test-bed and other measurement data	High, well known from operators and manufacturers	While there is some variation from engine to engine, the average figure is expected to have comparatively high accuracy.

Note: The confidence of the estimated fuel consumption of steam boilers must be categorized as moderate; however, it has little impact on the overall inventory.

Table 3.3 *Consensus estimate of fuel consumption (million tonnes) in 2007*

	Low bound	Consensus	High bound
Total fuel consumption*	279	333	400
International shipping†	223	277	344

* This estimate is based on all non-military ships > 100 GT and includes domestic shipping and fishing.
† Excluding domestic shipping, fishing, and military vessels.

Table 3.4 *Consumption of fuel (million tonnes) in 2007, by fuel type and combustion source*

	Total fuel consumption			International shipping		
	Low bound	Consensus	High bound	Low bound	Consensus	High bound
Residual fuel	215	257	308	172	213	265
Distillate fuel	64	76	92	51	64	79
Slow-speed engines	181	215	259	144	179	223
Medium-speed engines	92	110	132	73	91	113
Boilers	7	8	9	5	7	8

Table 3.5 *Fuel consumption (million tonnes) from 1990 to 2007*

Year	Total shipping			International shipping		
	Low bound	Consensus	High bound	Low bound	Consensus	High bound
1990	150	179	215	120	149	185
1991	157	187	224	125	155	193
1992	160	191	229	128	159	197
1993	166	199	239	133	165	205
1994	172	205	246	137	170	212
1995	177	211	254	141	176	218
1996	181	216	260	145	180	223
1997	191	228	274	153	190	236
1998	189	226	271	151	188	233
1999	193	230	276	154	191	238
2000	208	248	298	166	206	256
2001	209	250	300	167	208	258
2002	212	253	304	169	210	261
2003	226	270	325	181	225	279
2004	242	289	347	193	240	298
2005	255	304	365	204	253	314
2006	269	321	385	215	267	331
2007	279	333	400	223	277	344

FUEL-BASED EMISSION FACTORS FOR EXHAUST GASES

3.16 Fuel-based emission factors are conversion values that are used to calculate emissions, based on consumed fuel. In order to build the basic emission inventory in line with recognized standards, default emission factors prepared by IPCC and by the UNECE/EMEP CORINAIR programme are used, with the exception of NO_x, where the impact of the IMO NO_x regulation makes special analysis necessary. Emission factors that have been used for the 1990–2007 inventories are shown in Table 3.6. Three NO_x emission factors are shown:

1. for non-regulated engines (i.e. "Tier 0", older than 1 January 2000);
2. for engines subject to "Tier I" NO_x regulation (newer than 1 January 2000); and
3. a weighted fleet average that applies to the year 2007.

3.17 The weighting to determine the 2007 emission factor is based on the fraction of total power in the world fleet installed on or after 1 January 2000. This figure, 40.4%, is based on data from the Lloyd's Register – Fairplay database. Combustion in a boiler is continuous and occurs at a low pressure, very different from combustion in a diesel engine. Boilers generate significantly less NO_x per unit of fuel. Emission factors for boilers are not given by IPCC or CORINAIR guidelines. Based on a limited set of data, an emission factor of 7 kg/tonne was selected for emissions of NO_x from boilers. Further background data and analysis of NO_x emission factors is presented in paragraphs 4.5 to 4.11 of this report.

Table 3.6 *Fuel-based exhaust gas emission factors used in the 2007 inventory*

Emission		Emission factor (kg emitted/tonne of fuel)	Guideline reference
CO		7.4	CORINAIR
NMVOC		2.4	CORINAIR
CH_4		0.3	IPPC 2006/CORINAIR
N_2O		0.08	IPPC 2006/CORINAIR
CO_2	*Residual fuel oil*	3,130	IPPC 2006
	Marine diesel oil	3,190	IPPC 2006
SO_2	*Residual fuel oil (2.7% S)*	54	CORINAIR
	Marine diesel oil (0.5% S)	10	CORINAIR
NO_x	*Slow-speed diesel engines*	90 \ 78 (85)*	–
	Medium-speed diesel engines	60 \ 51 (56)*	–
	Boilers	7	–
PM_{10}	*Residual fuel oil*	6.7	CORINAIR
	Marine diesel oil	1.1	CORINAIR

* NO_x Emission factors: non-regulated\subject to IMO NO_x regulation (2007 average emission factor).

EMISSIONS OF EXHAUST GASES FROM SHIPPING, 1990–2007

3.18 Using the fuel estimates in paragraphs 3.9 to 3.15 and fuel-based emission factors in paragraphs 3.16 and 3.17, emissions of exhaust gases can now be calculated by multiplication. Results for shipping as a whole and for international shipping are shown in Table 3.7 and Table 3.8 respectively. These estimates are based on the consensus estimate for fuel consumption. The uncertainty in the estimate of the fuel consumption for shipping is carried over to the estimates of emissions. The bounding range is approximately ±20%. Figure 3.3 shows the distribution of fuel consumption and hence, to a certain degree, also emissions by ship categories.

Uncertainty in all emissions due to fuel consumption estimate: ±20%

Uncertainty in all emissions due to fuel consumption estimate: ±20%

Table 3.7 *Exhaust emissions (million tonnes) from total shipping, 1990–2007*

Year	NO_x	SO_x	PM	CO	NMVOC	CO_2	CH_4	N_2O
1990	14	7.9	1.0	1.3	0.4	562	0.05	0.01
1991	15	8.2	1.0	1.4	0.4	587	0.06	0.02
1992	15	8.4	1.0	1.4	0.5	598	0.06	0.02
1993	16	8.7	1.1	1.5	0.5	624	0.06	0.02
1994	16	9.0	1.1	1.5	0.5	644	0.06	0.02
1995	16	9.3	1.1	1.6	0.5	663	0.06	0.02
1996	17	9.5	1.2	1.6	0.5	679	0.07	0.02
1997	18	10	1.2	1.7	0.5	717	0.07	0.02
1998	18	10	1.2	1.7	0.5	709	0.07	0.02
1999	18	10	1.2	1.7	0.6	722	0.07	0.02
2000	19	11	1.3	1.8	0.6	778	0.07	0.02
2001	19	11	1.4	1.8	0.6	784	0.08	0.02
2002	19	11	1.4	1.9	0.6	794	0.08	0.02
2003	21	12	1.5	2.0	0.6	849	0.08	0.02
2004	22	13	1.6	2.1	0.7	907	0.09	0.02
2005	23	13	1.6	2.3	0.7	955	0.09	0.02
2006	24	14	1.7	2.4	0.8	1,008	0.10	0.03
2007	25	15	1.8	2.5	0.8	1,050	0.10	0.03

Table 3.8 *Exhaust emissions (million tonnes) from international shipping, 1990–2007*

Year	NO_x	SO_x	PM	CO	NMVOC	CO_2	CH_4	N_2O
1990	12	6.5	0.8	1.1	0.4	468	0.05	0.01
1991	12	6.8	0.8	1.2	0.4	488	0.05	0.01
1992	12	7.0	0.9	1.2	0.4	498	0.05	0.01
1993	13	7.3	0.9	1.2	0.4	519	0.05	0.01
1994	13	7.5	0.9	1.3	0.4	535	0.05	0.01
1995	14	7.7	1.0	1.3	0.4	551	0.05	0.01
1996	14	7.9	1.0	1.3	0.4	565	0.05	0.01
1997	15	8	1.0	1.4	0.5	596	0.06	0.02
1998	15	8	1.0	1.4	0.5	590	0.06	0.02
1999	15	8	1.0	1.4	0.5	601	0.06	0.02
2000	16	9	1.1	1.5	0.5	647	0.06	0.02
2001	16	9	1.1	1.5	0.5	652	0.06	0.02
2002	16	9	1.1	1.6	0.5	660	0.06	0.02
2003	17	10	1.2	1.7	0.5	706	0.07	0.02
2004	18	11	1.3	1.8	0.6	755	0.07	0.02
2005	19	11	1.4	1.9	0.6	795	0.08	0.02
2006	20	12	1.4	2.0	0.6	838	0.08	0.02
2007	20	12	1.5	2.0	0.7	870	0.08	0.02

EMISSIONS OF REFRIGERANTS FROM SHIPPING

3.19 Refrigerants are compounds, when used in a heat cycle, that undergo a phase change from a gas to a liquid and back. The two main uses of refrigerants on board ships are for refrigeration/freezers of cargo and provisions and in air conditioners. The most common refrigerants used on board ships are [33]:

- HFCs (hydrofluorocarbons);
- CFCs (chlorofluorocarbons);

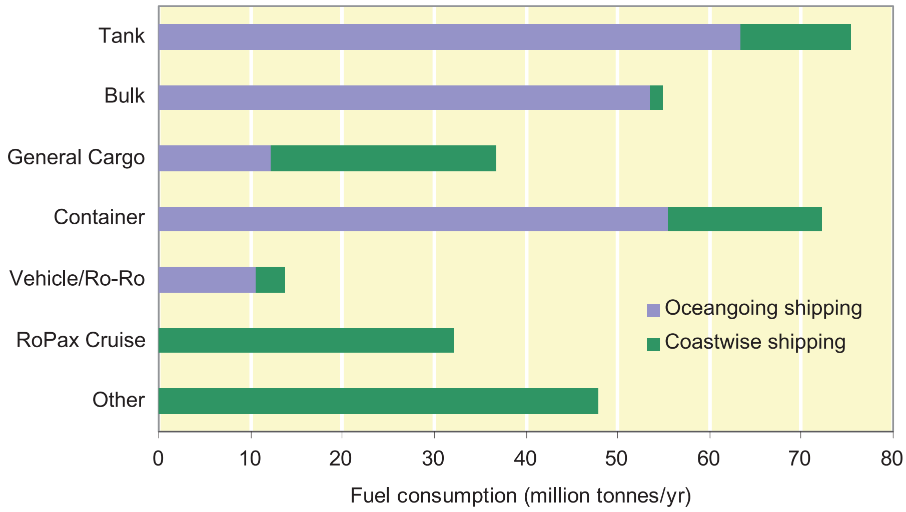


Figure 3.3 *Fuel consumption, separated into consumption by main categories of vessel and assumed typical types of operation (Coastwise shipping is mainly ships < 15,000 dwt, RoPax, Cruise, Service and Fishing)*

- HCFC-22, difluorochloromethane (which is also a CFC); and
- R717 (ammonia).

3.20 HCFC-22 and CFCs are a cause of ozone depletion. Regulation 12 of MARPOL Annex VI prohibits deliberate emissions of these and other ozone-depleting substances. Regulation 12 also prohibits new installations using ozone-depleting substances, except that HCFCs may be used until 1 January 2020. HCFC-22, HFCs and CFCs have strong ozone-depletion potentials, but also have significant potential to cause global warming.

3.21 Refrigerants are emitted to the atmosphere through leaks that occur during the operation and in conjunction with the maintenance of equipment. Refrigerant gas may also be released when the unit is scrapped. Emissions of refrigerants from international shipping are related to three main sources:

1. refrigeration plants on reefer ships;
2. air conditioning and refrigeration of provisions, etc. on all types of ships; and
3. refrigerated containers carried on board ships.

3.22 The most comprehensive and recent review of emissions of refrigerants from ships is found in the 2006 assessment report of the United Nations Environment Programme (UNEP). This report is prepared by the UNEP Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC) [33]. The following section is based mainly on this report.

REEFER SHIPS

3.23 Almost 90% of all reefer ships still use HCFC-22. The refrigeration systems of about 10% of all reefer ship run on HFCs such as HFC-134a (mainly), R404A and R407C or R410A, mostly in indirect systems, in which charges of 500 kg to 1,000 kg of refrigerant are employed. Some HFC-23 is used in freezer applications. Since 1993 there has been an increase in the number of R717 systems in new vessels. Emissions from older systems are still high, and are estimated to be 20% per year, while emissions of 5–10% per year can be achieved by using indirect systems that have a smaller initial charge [33].

CONTAINERS

3.24 Transport of refrigerated goods in containers on board ships has been increasing rapidly in recent years. The 2005 refrigerated container fleet is approximately 750,000, equivalent to 1,270,000 TEU. These containers are used both on ships and on land. There are still about 50,000 units using HCFC-22, but no new HCFC-22 systems are built. About 700,000 units use HFC-134a with a small proportion of R404A. An estimate of emissions from containers as a whole is provided in Table 3.9. How much of these emissions occurs while the containers are on board ships is not known.

AIR-CONDITIONING AND REFRIGERATION SYSTEMS

3.25 Nearly all merchant vessels have refrigeration systems for their provision rooms and their air-conditioning equipment. Seventy to eighty per cent of the fleet still use HCFC-22 as refrigerant, while the rest use HFCs, with some R717 and R717/R744 cascade systems on fishing vessels. There are also some remaining CFC-based systems.

3.26 HFC-134a, R404A and R507 are established in the market and readily available. Estimated annual leakage rates vary between 1% and 100%, depending on the data source. It is generally agreed in the industry that reduced leakage rates can be achieved, even in the rough environment of seaborne transport, if appropriate equipment is used, and it is maintained and controlled by trained personnel. However, appropriate equipment and proper maintenance procedures are not always employed. This is particularly the case for equipment that is considered to be non-essential, as is often the case for air-conditioning or refrigeration systems.

3.27 There is a clear drop in consumption of HFC refrigerant in the cruise industry due to improved maintenance routines, as a consequence of the more stringent environmental rules that have been applied in the US (EPA 608). There is also strong growth in sales of refrigerant recovery equipment as well as a growing demand for inspections and repairs of refrigeration systems. Changeover solutions for HCFC-22 to ozone-friendly HFCs are being implemented, in order to encourage operating companies to prepare for the future.

ESTIMATED EMISSIONS FROM SHIPS

3.28 Emissions of refrigerants from shipping and other modes of transport have been estimated in the 2006 assessment report of the United Nations Environment Programme. Some of the results of this assessment are shown in Table 3.9 and Figure 3.4. These figures refer to 2003. These emissions are more closely linked with composition/structure than activity. They cannot therefore be forecast or backcast in the same way as can emissions of exhaust gases.

Table 3.9 *Emissions of refrigerants in 2003, UNEP [33]*

	Refrigerant emissions (tonnes)			
	HCFC-22	**HFC**	**R717**	**CFC**
Reefer ships	600	15	3	0
Merchant marine, naval, fishing	2,500	400	4	15
Containers (including emissions from land and sea)	38	555	0	15
Road	1,000	3,780	0	1,000
Rail	5	15	0	30
Total transport	**4,143**	**4,765**	**7**	**1,060**
Total shipping (reefer + merchant)	3,100	415	7	15

NON-EXHAUST EMISSIONS OF VOCS FROM SHIPS

3.29 Volatile organic compounds (VOCs) may be emitted from cargo carried on board ships. This study covers emissions of CH_4 and NMVOC that occur during transport of crude oil. VOCs may also be emitted by product carriers. Emissions arising from transport of LNG are very small, since these tanks are not vented to the atmosphere during operation.

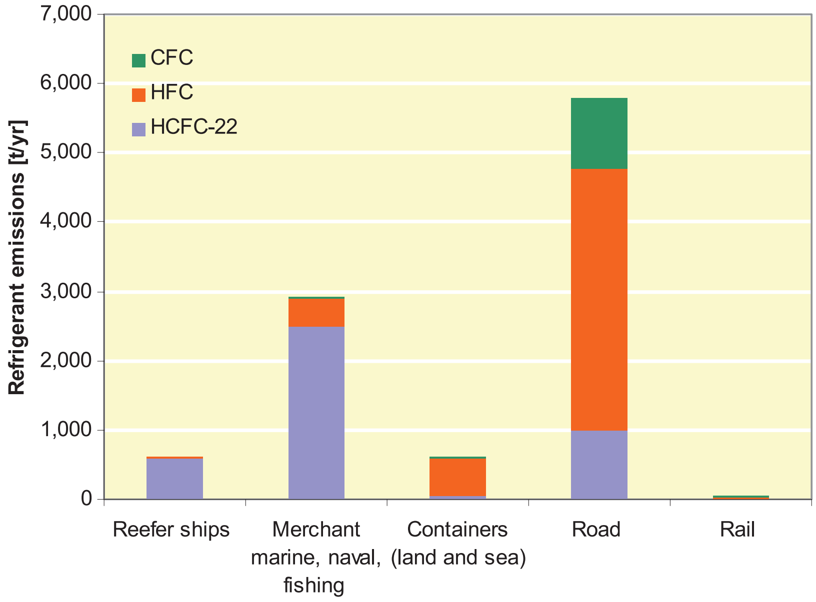


Figure 3.4 *Emissions of refrigerants from transport in 2003, UNEP [33]*

3.30 Emissions of VOCs occur mainly during loading and in transit. The part of the VOC emission that is generated during loading may be counted in inventories of national emissions [37]. Paragraphs 3.29 and 3.30 assess the emissions of VOCs that occur during transport of crude oil, by combining available data and existing literature.

ESTIMATES OF EMISSIONS OF VOCS, BASED ON VOLUMES OF CARGO RECEIVED AND DELIVERED

3.31 The Energy Institute Hydrocarbon Management Committee 4A (HMC-4A) collects and analyses world-wide shipping data for oil. The database for 2006 contains complete loading and discharge data for 40% of the global volume of crude oil that is transported by ships. A summary of the received data has been published in the October 2007 issue of *Petroleum Review* [34].

3.32 The database presents data for loss of Net Standard Volume (NSV) (= NSV at Bill of Lading minus NSV at outturn), which is calculated from data for individual voyages. The NSV is the volume of crude oil, corrected to 60°F, with quantities of sediment and of water deducted. The global mean net loss of NSV for 2006 is 0.177% of the loaded volume. The loss of NSV is small compared to the typical accuracy of 2% of each of the measurements of volume from which NSV is calculated, and it is only by having a large number of samples that it is possible to calculate the loss of NSV. The standard deviation for the NSV loss that was reported in 2006 is 0.31%.

3.33 Since these data only provide the change in volume due to release of VOCs, it is not possible to specify how much occurs during different phases (loading, transit, etc.), and it is not possible to specify what fraction of the loss is CH_4 and what is NMVOCs.

3.34 The loss of mass due to emission of VOCs is somewhat smaller than the loss of NSV. It is the light ends of the crude oil that are lost as VOC emissions. The mean molecular weight of the discharged crude oil will therefore become slightly higher than the molecular weight of the loaded cargo. Referred to the same temperature, the density of the discharged crude oil will therefore be slightly higher than that of the loaded cargo.

3.35 Calculation of some typical examples indicates that losses of mass are between 25% to 40% smaller than the volumetric losses. Assuming that the mean loss of mass is 30% smaller than the loss of volume, the NSV loss of 0.177% found in [34] corresponds to a mass loss of 0.124%.

3.36 According to BP's global energy statistics [36], transport of crude oil in 2006 was 1,941 million tonnes. The corresponding emission of VOCs (CH_4 + NMVOCs) would then correspond to ~2.4 million tonnes.

ESTIMATES BASED ON VAPOUR PRESSURE OF CRUDE OILS AT LOADING AND DISCHARGE

3.37 Emissions of VOCs have been estimated by means of a methodology in which the average vapour pressure of crude oils at loading and at discharge is used as the input to a model cited by A.P.I. Bulletin No. 2518 to obtain an average VOC emission loss for the voyage alone. The programme was mainly based on the reception of crude oil samples and data from 32 participating vessels.

3.38 Using this methodology, the VOC emission loss for the voyage alone is estimated to be 0.26 weight per cent of the loaded cargo [35]. This is about twice as high as the estimate based on NSV reported in [34], where losses during loading and discharge are included. This result is also not supported by direct measurements, as discussed below, or by a scientific analysis, using standard emission factors [6].

DIRECT MEASUREMENTS OF VOC/NMVOC EMISSIONS

3.39 Over the past 20 years, MARINTEK/SINTEF has carried out a number of measurements of the emissions of VOCs that occur when loading different shuttle tankers on different offshore oil-fields in the North Sea. These have been performed by direct measurement of flow, absolute pressure, temperature and composition of gas flowing from the cargo tanks to the atmosphere. Figure 3.5 shows VOC emission factors (defined as VOC emission in per cent of cargo) for almost 70 individual measurements of emissions. For two of the oil-fields, there exist around 20 measurements for each.

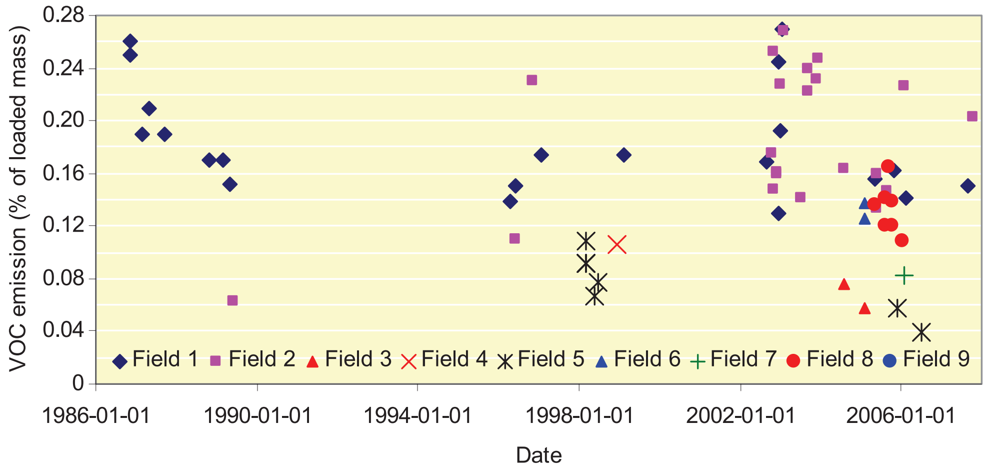


Figure 3.5 *VOC emission factor measured during offshore loading in the North Sea*

3.40 The emission of VOCs is very variable. Measured values vary from 0.04 mass per cent to 0.27 mass per cent. Even for the same oil-field, there is a 1:2 variation in VOC losses. One important factor that distinguishes offshore loadings from most onshore terminal loadings is the movement of the vessel during the loading. It may vary from almost no movement at all to very large angles of rolls and pitch. It is therefore probably the factor most responsible for the large variation of emission of VOCs for the same oil-field. Different compositions and temperatures of crude oil are also important parameters that contribute to variation in VOC emissions. Also, the amount of VOCs in the cargo tanks prior to loading may vary significantly and therefore contribute differently to the loss of VOCs during loading.

3.41 To date, there has been no attempt to calculate an average VOC loss factor from these measurements. It would involve some kind of weighting of the individual values, which would be a lengthy and uncertain process. Neglecting the weighting, the mean value of the values in Figure 3.5 becomes somewhere around 0.18 mass per cent. This is somewhat larger than the mean VOC loss from the NSV approach in [34], even if the latter also includes losses during transportation and discharge, which may be due to the fact that most of the data entries to the [34] database are from loadings at onshore terminals.

3.42 Because MARINTEK does measure the composition of the emitted gas, it is possible to separate the VOC loss into methane loss and Non-Methane VOC (NMVOC) loss. The mass fraction of methane loss compared to total VOC loss does vary from 0 to 0.5. The latter is from an oil-field with an unusually high content of methane in the crude. For most of the fields, however, this fraction lies between 0.02 and 0.10.

3.43 For some of the cases shown in Figure 3.5, the NMVOC emission on the laden voyage was also measured. The voyages are short, typically between 0.5 and 4 days. The NMVOC emission on the laden voyage varied between 0% and 10% of the emission of NMVOC during loading, depending on such factors as the composition and temperature of the crude oil and the sea state.

PUBLISHED ASSESSMENT BASED ON STANDARD EMISSION FACTORS

3.44 Endresen *et al.* [6] have modelled VOC emissions arising from transport of crude oil. This study provides the geospatial distribution of VOC emissions from shipping, and it has been used in the analysis of impact on climate in Chapter 8.

3.45 Endresen *et al.* [6] quantify the amount and location of the emissions of VOCs by means of VOC emission factors for crude oil during loading, transport and unloading and an estimate of the transport pattern. The VOC emission factors for unloading and for transport are based on emission factors from US-EPA known as the "AP-42 emission factors" [38] (129 mg/litre and 150 mg/week/litre respectively). The VOC emission factor during loading is based on a review of data for emission of hydrocarbons and factors presented by EMEP/CORINAIR (0.1% of loaded mass). They also include some emissions of VOCs from the main propulsion engine of the vessels (0.3 kg of methane and 2.4 kg of NMVOC per tonne of fuel).

3.46 With the estimated transport pattern, they get a round-trip VOC emission of 0.15% of loaded mass. Their simulation model gives the distribution of VOC emissions as 70% during loading, 27% at voyage and 3% during unloading.

ASSESSMENT OF EMISSIONS OF VOCS FROM TRANSPORT OF CRUDE OIL

3.47 Considering the available data, the Energy Institute database was selected as the best basis for representative data on overall emissions. The estimated split between CH_4 and NMVOC is based on MARINTEK measurements, which typically range from 0.02% to 0.1%. This latter assessment is highly uncertain, since the data from MARINTEK for the North Sea may not be representative of the global situation. The estimates are given in Table 3.10.

Table 3.10 *Losses of VOCs from transport of crude oil during 2006*

	Million tonnes
NMVOC	2.3
CH_4	0.14
Total	2.4

EMISSIONS OF SULPHUR HEXAFLUORIDE (SF_6) FROM SHIPS

3.48 Sulphur hexafluoride (SF_6) is a synthetically produced gas with an extremely high global warming potential (GWP 23 900). The main application is as an insulator and arc switching medium in high-voltage components within the power sector. Although the main consumers of SF_6 are power suppliers, network distributors and some large-scale industrial power consumers, the gas is also used as a sound insulator in windows and as a tracer gas, commonly in oil wells [30].

3.49 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.

EMISSIONS OF PFCS FROM SHIPS

3.50 PFCs are highly potent greenhouse gases having global warming potentials in the thousands. The chemical substance PFOS (perfluorooctane sulphonate) belongs to a large family of compounds known as PFCs. PFOS-related substances have been used in a variety of industrial applications and consumer products since the 1950s, mainly due to their ability to create particular surface properties. Applications range from textile and paper treatment, and a variety of other areas within the coating industries, to chromium plating, hydraulic fluids (for aviation) and fire-fighting foam; in the latter, it enables film formation.

3.51 The main application on board ships that is of relevance is considered to be fire-fighting foams of the type AFFF (Aqueous Film-Forming Foam). Although the use of PFOS in new AFFFs has been phased out by major manufacturers in recent years, stockpiles of foams containing PFOS still exist on board ships and may be used. PFOS-containing AFFFs could, in principle, be applied on board a range of ship types, but the larger volumes are usually installed on ships carrying flammable fluids, and on vessels with a helicopter deck. Volumes normally range from some 100 litres to 10,000 litres, depending on the type and size of the ship. The foam is typically stored in one tank, serving a main system, potentially with additional smaller and separate devices (for example 20 litres), usually in the machinery room(s). PFOS is normally at concentrations within the range 0.017–0.037 kg/litre of foam, which means that the amount of PFOS on a single ship can range between 0.3 kg and 400 kg. The PFOS is enclosed in the fire-fighting systems and is only released when the system is deployed. There are no regular emissions of PFCs from ships, and the leakage is regarded as negligible. The emission of PFOS is most relevant in the process of recycling the ship, where the fire-fighting system can be emptied if it is not properly handled [31].

SUMMARY OF PRESENT-DAY EMISSIONS FROM SHIPPING

3.52 Emissions of exhaust gases from ships have been estimated, using an activity-based approach. Standard emission factors from inventory guidebooks have been used to the greatest possible extent. Emissions of refrigerants are taken from UNEP assessment reports, while emissions of VOCs from transport of crude oil have been estimated in this study by combining data from different sources. A summary of the estimated emissions from total shipping for 2007 is shown in Table 3.11. Ship exhaust is generally the more important source of emissions, although emissions of VOCs from the transport of crude oil are an important source of CH_4 and NMVOC. Note that the figure for emissions of refrigerants refers to 2003 (this is the most recent figure available).

Table 3.11 *Summary of emissions (million tonnes) from total shipping in 2007**

	Ship exhaust	Refrigerant	Transport of crude oil	Total
CO_2	1,050	–	–	1050
CH_4	0.10	–	0.14†	0.24
N_2O	0.03	–	–	0.03
HFC	–	0.0004	–	0.0004
PFCs	–	–	–	–
SF_6	–	–	–	–
NO_x	25	–	–	25
NMVOC	0.8	–	2.3	3.1
CO	2.5	–	–	2.5
PM	1.8	–	–	1.8
SO_x	15	–	–	15

* HFC numbers are valid for 2003. Transport of crude oil: 2006 figures.
† High uncertainty.

REFERENCES

1 Corbett, J.J. and Köhler, H.W. 2003. "Updated emissions from ocean shipping". *J. Geophys. Res*. 108 (D20), 4650, doi:10.1029/2003JD003751.

2 Corbett, J.J., Firestone, J., and Wang, C. 2007. "Estimation, validation, and forecasts of regional commercial marine vessel inventories", Final Report for the California Air Resources Board and the California Environmental Protection Agency and for the Commission for Environmental Cooperation in North America, ARB Contract Number 04–346.

3 Eyring, V., Köhler, H.W., van Aardenne, J., and Lauer, A. 2005. "Emissions from international shipping: 1. The last 50 years". *J. Geophys. Res*. 110, D17305, doi:10.1029/2004JD005619.

4 Input from the four subgroups and individual experts to the final report of the Informal Cross Government/ Industry Scientific Group of Experts. IMO document BLG 12/INF.10.

5 Endresen, Ø., Sørgård, E., Behrens, H.L., Brett, P.O., and Isaksen, I.S.A. 2007. "A historical reconstruction of ships' fuel consumption and emissions". *J. Geophys. Res*. 112, D12301, doi:10.1029/2006JD007630.

6 Endresen, Ø., Sørgård, E., Sundet, J.K., Dalsøren, S.B., Isaksen, I.S.A., Berglen, T.F., and Gravir, G. 2003. "Emission from international sea transportation and environmental impact". *J. Geophys. Res*. 108, D174560, doi:10.1029/ 2002JD002898.

7 Fearnleys. 2007. *Fearnleys Review 2007: The Tanker and Bulk Markets and Fleets*, Oslo, Norway.

8 Gunner, T.J. 2007. "Shipping, CO_2 and other Air Emissions", Technical workshop meeting on emissions from aviation and maritime transport, Oslo, Norway, October 2007. http://www.eionet.europa.eu/training/ bunkerfuelemissions

9 Lloyd's Register – Fairplay (LRF), 2006. Extracts from the World merchant fleet database for 2001 to 2006 (all civil ocean-going cargo and passenger ships above or equal to 100 GT), provided by Lloyd's, UK.

10 Olivier, J.G.J. and Peters, J.A.H.W. 1999. "International marine and aviation bunker fuel: trends, ranking of countries and comparison with national CO_2 emissions". Netherlands Environmental Assessment Agency. RIVM report 773301 002.

11 Olivier, J.G.J., Berdowski, J.J.M., Peters, J.A.H.W., Bakker, J., Visschedijk, A.J.H., and Bloos, J.P.J. 2001. "Applications of EDGAR. Including a description of EDGAR 3.0: reference database with trend data for 1970–1995". RIVM, Bilthoven. RIVM report 773301 001/ NRP report 410200 051.

12 Skjølsvik, K.O., Andersen, A.B., Corbett, J.J., and Skjelvik, J.M. 2000. "Study of greenhouse gas emissions from ships" (MEPC 45/8: Report to International Maritime Organization on the outcome of the IMO Study on Greenhouse Gas Emissions from Ships. MARINTEK Sintef Group, Carnegie Mellon University, Center for Economic Analysis, and Det Norske Veritas: Trondheim, Norway).

13 Thomas, R., Lauretis, R.D., Fontelle, J.-P., Hill, N., Kilde, N., and Rypdal, K. 2002. "Shipping Activities", Chapter B842, in *EMEP/CORINAIR Emission Inventory Guidebook – October 2002 UPDATE*, edited by K. Lavender, G. Reynolds, A. Webster, and K. Rypdal, European Environment Agency, Copenhagen, Denmark.

14 Wang, C., Corbett, J.J., and Firestone, J. 2008. "Improving spatial representation of global ship emissions inventories". *Environmental Science & Technology* 42, 193–199, doi:10.1021/es0700799.

15 Corbett J.J. and Fischbeck P.S. 1997. "Emissions from Ships". *Science* 278 (5339), 823–824, doi:10.1126/ science.278.5339.823.

16 Data provided by Lloyd's Register – Fairplay Research, Sweden.

17 Data compiled by DonChool Lee, Mpoko National Maritime University, Korea.

18 Diesel & Gas Turbine Worldwide. 2005. Diesel & Gas Turbine Publications, 20855 Watertown Road, Suite 220, Waukesha, WI 53186, USA.

19 Scott, R. 1994. "IEA: The first twenty years". Paris, France, Organisation for Economic Co-operation and Development (OECD).

20 ICF Consulting. 2005. "Best Practices in Preparing Port Emission Inventories: draft for review". Browning, L. and E.P.S.L. Bailey, K. Fairfax, Virginia, Prepared for Office of Policy, Economics and Innovation, United States Environmental Protection Agency.

21 UNFCCC and Subsidiary Body for Scientific and Technological Advice. 2004. "Methodological issues relating to emissions from international aviation and maritime transport; Note by the secretariat". Bonn, Germany, 16–25 June United Nations Framework Convention on Climate Change, Subsidiary Body for Scientific and Technological Advice: FCCC/SBSTA/2004/INF.5.

22 International Energy Agency. 1987. Energy Statistics 1970–1985 and Main Series from 1960. Paris, France, Organisation for Economic Co-operation and Development.

23 Houghton, J.T., Meira Filho, L.G. *et al.*, editors. 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Bracknell, UK, IPCC WGI Technical Support Unit.

24 Corbett, J.J. and Fischbeck, P.S. 2000. "Emissions from waterborne commerce vessels in United States continental and inland waterways". *Environmental Science & Technology* 34, 3254–3260, doi:10.1021/es9911768.

25 CIMAC – International Council of Combustion Engines http://www.cimac.com

26 IEA Data Services, 2007 Energy Balances and Energy Statistics for OECD and non-OECD Countries.

27 Energy Information Administration. International Energy Annual, table 31 – various years: http://www.eia.doe.gov/

28 *International Convention for the Safety of Life at Sea (SOLAS)*, 1974. Chapter V – Safety of navigation.

29 Endresen, Ø., Bakke, J., Sørgård, E., Berglen, T.F. and Holmvang, P. 2005. "Improved modelling of ship SO_2 emissions – a fuel-based approach". *Atmospheric Environment* 39, 3621–3628.
30 Bessede, J.L., Buescher, A., Marshall, R., Montillet, G.F., and Stelter, A. 2006. EPA San Antonio 2006 Version 2.8. "Limiting SF_6 gas emissions by optimization of design and handling over the life cycle of HV switchgear".
31 Norwegian Pollution Control Authority. December 2005. Kartlegging av PFOS i brannskum. TA-2139/2005, ISBN 82–7655–275–7 (978–82–7655–275–1).
32 Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC), United Nations Environment Programme 1998 RTOC Assessment report. http://ozone.unep.org/teap/Reports/RTOC/index.shtml
33 Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC), United Nations Environment Programme 2006 RTOC Assessment report. http://ozone.unep.org/teap/Reports/RTOC/index.shtml
34 *Petroleum Review*. October 2007, http://www.oil-transport.info/Voyage_data/PetRev.pdf
35 Gunner, T. The physical behaviour of crude oil influencing its carriage by sea (CRUCOGSA), Vestfold College, Norway, 2000.
36 Statistical Review of World Energy. BP, www.bp.com, Accessed 2008 http://www.bp.com/productlanding.do?categoryId=6929&contentId=7044622
37 2006 IPCC Guidelines for National Greenhouse Gas Inventories. http://www.ipcc-nggip.iges.or.jp/public/2006gl/index.html
38 U.S. Environmental Protection Agency. "Emissions factors and AP 42" http://www.epa.gov/ttn/chief/ap42/

4

Reductions in emissions achieved by implementation of MARPOL Annex VI

4.1 This chapter discusses the progress in reducing emissions of greenhouse gases and other relevant substances that has been achieved through implementation of IMO regulations. Due to the increase in seaborne transport, absolute emissions have tended to increase over time. However, in relation to transport work done, there have been reductions. Generally speaking, exhaust emissions will be reduced when energy efficiency is improved. Therefore, the historical development in vessel efficiency presented in Chapter 9 indicates a reduction of emissions in relation to transport work done additional to what is presented in this chapter.

REGULATION 12 – OZONE-DEPLETING SUBSTANCES

4.2 Regulation 12 of MARPOL Annex VI prohibits deliberate emissions of ozone-depleting substances. Regulation 12 also prohibits new installations that use ozone-depleting substances, except that HCFCs may be used until 1 January 2020.

4.3 Estimates of emissions of refrigerants from ships have been made by UNEP as part of its 1998 [1] and 2006 [2] assessment reports. A comparison of the estimates in these assessments is provided in Table 4.1 and Figure 4.1. These estimates are based on the amounts of refrigerant that have been supplied to ships in order to replace lost refrigerant. A very significant reduction in emissions of CFCs and HCFCs

Table 4.1 *Reduction in estimated annual emissions (tonnes) of refrigerants from ships**

	1998 RTOC Total	2006 RTOC Total	Reduction
CFC	750	15	735 (98%)
HCFC-22	14,000	3,100	10,900 (78%)
HFC	100	415	–315 (–315%)

* Merchant marine, naval, fishing and reefer.

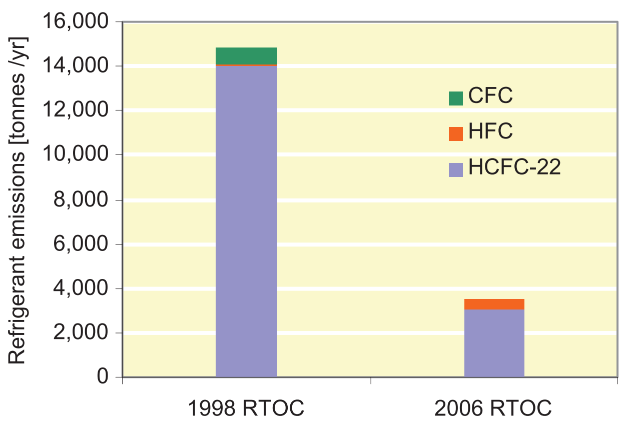


Figure 4.1 *Estimated emissions of ozone-depleting substances [UNEP]*

has been achieved during this period. Replacement of CFCs and HCFCs, on the other hand, has resulted in increased use and emissions of HFCs. The emissions data shown in the 2006 RTOC report [2] refer to 2003; however, a base year is not available in the 1998 report [1]. Since ozone-depleting substances other than HCFCs are prohibited with the coming into force of Annex VI, emissions of CFCs and HCFCs are expected to be virtually eliminated.

4.4 The revised Annex VI [3] specifies that all ships must maintain a list of equipment containing ozone-depleting substances and that every ship above 400 GT that has rechargeable systems must maintain an Ozone-Depleting Substances Record Book. This will permit better operational control and benchmarking of emissions, increase awareness and help to further reduce emissions.

REGULATION 13 – NITROGEN OXIDES (NO_X)

4.5 Emissions of NO_x are addressed in regulation 13 of Annex VI. The original Tier I limit on NO_x emissions applies to engines built on or after 1 January 2000. In line with interim guidelines communicated through MEPC/Circ.344 [4], engine builders adhered to the regulation prior to its enforcement.

4.6 To analyse the effect of this regulation, it is necessary to assess typical emission levels before and after 1 January 2000. Emissions of NO_x are very dependent on the conditions under which the fuel is burned in the engine. The NO_x emissions are therefore specific to engine type, conditions and settings. NO_x emissions also differ with fuel type and ambient conditions. This results in a significant scatter in the data of NO_x emissions. For the purpose of establishing emissions inventories, it is usual to distinguish between slow-speed diesel (SSD) engines and medium-speed diesel (MSD) engines.

4.7 The introduction of a tax on NO_x emissions from domestic shipping in Norway since 1 January 2007 has resulted in emissions from a significant number of engines being measured. These previously unpublished data were made available to the study by the Norwegian Maritime Administration. These data, data from the Lloyd's Marine Emissions study and from other MARINTEK measurement campaigns were combined to produce a joint dataset of NO_x emissions from existing ships. This dataset contains a total of 121 measurements, 96 of which are for medium-speed engines. Emission factors derived from this dataset are shown, together with data from two other key references, in Table 4.2. The data agree fairly well, except that the MSD data derived from the combined Swedish Environmental Research Institute (IVL) and Lloyd's data seem slightly high.

Table 4.2 *NO_x emission factors (kg/tonne of fuel) for engines installed prior to 1 January 2000*

SSD	MSD	Source
87	57	Lloyd's Marine Emissions study (1995) [5]
89*	65*	Combination of IVL and Lloyd's data presented in "Quantification of emissions from ships associated with ship movements between ports in the European Community" 2002 [6]
90[a]	60[b]	Data compiled for this IMO study

* It is possible that some engines were built after 1 January 2000.
[a] 25 engines, including seven engines from Lloyd's Marine Emissions study.
[b] 96 engines, including 19 engines from Lloyd's Marine Emissions study.

4.8 Onboard measurements of exhaust gas emissions are mainly performed on engines where other data, such as test-bed certificate data, are not available. For this reason, the dataset of on board measurements contains primarily data on engines that were built before 2000. In order to assess the emission factor of engines new-built after 1 January 2000 (and thus subject to Tier I NO_x emission limits), emission factors were calculated on the basis of engine certificate test data obtained from the DNV certificate database. This database contains test-bed emissions data for parent engines with DNV class that were installed on or after 1 January 2000. Data from this database are shown in Table 4.3.

4.9 As Table 4.3 shows, the emission factor for engines subject to MARPOL NO_x regulations is 10% lower, on average, than current EMEP/CORINAIR guidebook values. Test-bed measurements of

Table 4.3 *Test-bed emission factors for NO_x – engines newer than 1 January 2000**

	SSD	MSD
Average NO_x emission factor (kg/tonne of fuel)	78.2	51.4
Standard deviation in data	11.0	7.6
Number of weighted measurements	1,057	3,093
EMEP/CORINAIR guidebook NO_x emission factor (kg/tonne of fuel)	87	57
Difference	–10%	–10%

* Data based on EIAPP certificates and corresponding technical files.

emissions from engines are made with distillate fuel and on load points that differ from real engine operating loads. Specific emissions on board ships may be higher, for instance due to nitrogen in the fuel. On the other hand, fuel consumption on board may also be higher, which could counteract the other increase in terms of emission factor (emissions per unit of fuel used). It is thus not clear in which, if any, direction test-bed data would be biased. There is thus no obvious possibility to correct the test-bed data to an "on board" equivalent, and the test-bed values are used "as is" to represent engine emissions.

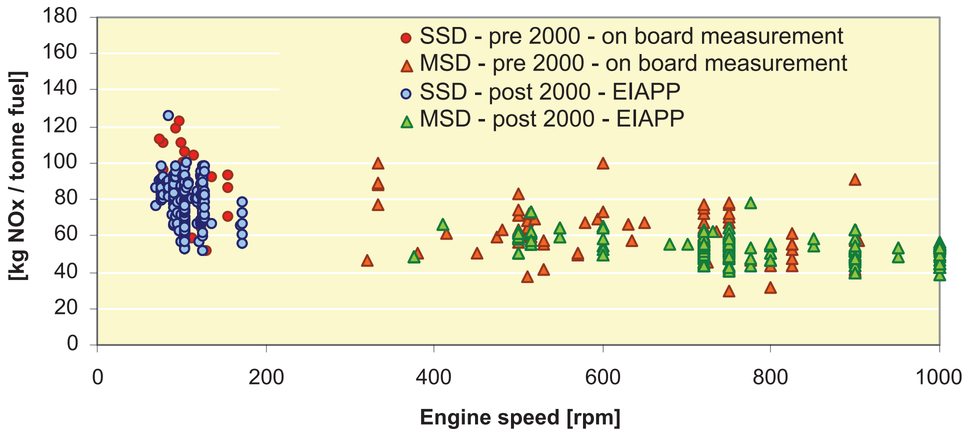


Figure 4.2 *NO_x emission factors from measurement and from EIAPP certificates*

4.10 In order to establish emission factors for the fleet that would take into account the difference between pre-2000 (Tier 0) and post-2000 (Tier I) engines, weighted average values were established, using the total power in the fleet installed before and after 2000, based on data from Lloyd's Register – Fairplay. Due to the very rapid expansion of the fleet in the post-2000 period, the post-2000 share of engine power is quite significant, at 40.4% (see Table 4.4). Linear interpolation was used to establish emission factors for the years 2000–2006.

Table 4.4 *NO_x emission factors used*

	SSD	MSD
Tier 0 average NO_x factor (kg/tonne of fuel)	89.5	59.6
Tier I average NO_x factor (kg/tonne of fuel)	78.2	51.4
Power installed post-2000 (% total kW)	40.4%	
2007 NO_x (kg/tonne of fuel)	84.9	56.3
2000–2006 NO_x emission factor	Linear interpolation for each year*	

* See Table 4.5.

4.11 Using fuel consumption data presented in chapter 3, NO_x emissions were calculated for a hypothetical no-regulation scenario in which Tier 0 emission factors were assumed to apply also after 1 January 2000. The results are shown in Figure 4.3 and Table 4.5. The annual reduction rose every year due to a larger fraction of engines in the world fleet being subject to Tier I regulation. It is estimated that the

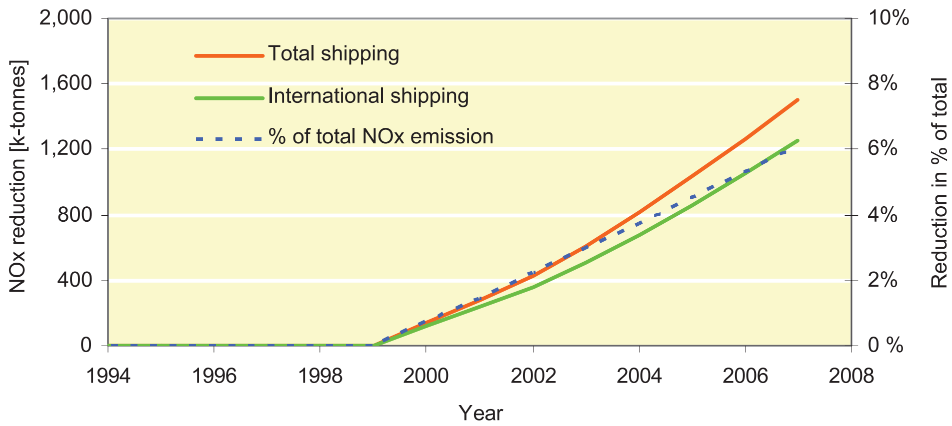


Figure 4.3 *NO_x reductions achieved by regulation 13*

Table 4.5 *NO_x reductions (thousand tonnes) achieved by regulation 13*

Year	Total	International	%
2000	140	116	0.7
2001	282	235	1.5
2002	428	356	2.2
2003	610	508	3.0
2004	816	679	3.7
2005	1,031	857	4.5
2006	1,268	1,055	5.3
2007	1,504	1,251	6.1
Total 2000–2007	5,940	4,941	3.4

introduction of regulation 13 has resulted in a reduction of about 6% of NO_x emissions from shipping in 2007 compared to a no-regulation scenario.

REGULATION 14 – SO_X

4.12 Emissions of SO_x are addressed in regulation 14 of Annex VI, which caps sulphur emissions globally at 4.50%, and less in SO_x Emission Control Areas (SECAs). In a SECA, the sulphur content of fuel oil used on board ships must not exceed 1.50% by mass. As an alternative, ships may use an exhaust gas scrubbing system. However, this is only done currently in the form of prototype testing on a very limited number of ships.

4.13 The content of sulphur in marine fuels is monitored in IMO's Sulphur Monitoring Programme, which is mandated under MARPOL Annex VI. In this programme, data are collected from test laboratories that analyse fuel samples on a commercial basis. Results from the programme are reported to MEPC annually [7].

4.14 It is widely acknowledged that the global limit of 4.50% of sulphur does not practically reduce global sulphur emissions, since a sulphur content exceeding this level was very rarely found in fuels before this regulation came into force. In the rare case that the sulphur level does exceed 4.50%, it will only exceed the limit by a small margin, and hence the fuel can easily be blended down, using a relatively low-sulphur fuel. However, the SECAs do have a significant impact.

4.15 Two SECAs are in operation. These are:

1. the Baltic Sea SECA, in force since 19 May 2006; and
2. the North Sea SECA, in force since 22 November 2007.

4.16 These regional regulations help reduce SO_x emissions in these particularly sensitive areas, where shipping is also very dense. In order to give an estimate of the reductions in emission that are achieved, it is necessary to quantify:

- the amount of fuel used in the SECA (for estimating global average reduction);
- the average sulphur content of the fuel that is used within the SECA; and
- the probable sulphur content of fuel in the absence of MARPOL regulation 14.

4.17 2008 is taken as the base year for the estimates, since this is the first year in which both SECAs were in force throughout the year. The following assumptions were used to calculate the estimate:

– 2008 global fuel consumption (see Table 4.6) is based on the 2007 consensus estimate and the growth trend for the A1B scenario (A1B refers to scenarios as discussed in Chapter 7);
– fuel consumption within SECAs, which is estimated as 8% of global fuel consumption (this is based on an estimate that was made for the European Commission) [7]; and
– levels of sulphur in fuel, as shown in Table 4.7.

Table 4.6 *Estimated fuel consumption (million tonnes) (2008)*

	HFO*	MDO†	Total
SECA	21	6	27
Non-SECA	241	71	312
Total	262	77	339

* HFO: Heavy fuel oil.
† MDO: Marine diesel oil.

Table 4.7 *Estimated average sulphur content of fuels (2008)*

	HFO	MDO
SECA*	1.5%	0.5%
Non-SECA*	2.7%	0.5%

* Non-SECA factors are also used in a hypothetical no-regulation scenario.

Table 4.8 *Estimated emissions (million tonnes) of SO_2 (2008)*

	Hypothetical baseline	MARPOL Annex VI	Reduction
Global total	14.9	14.4	3.4%
SECA	1.2	0.7	42%

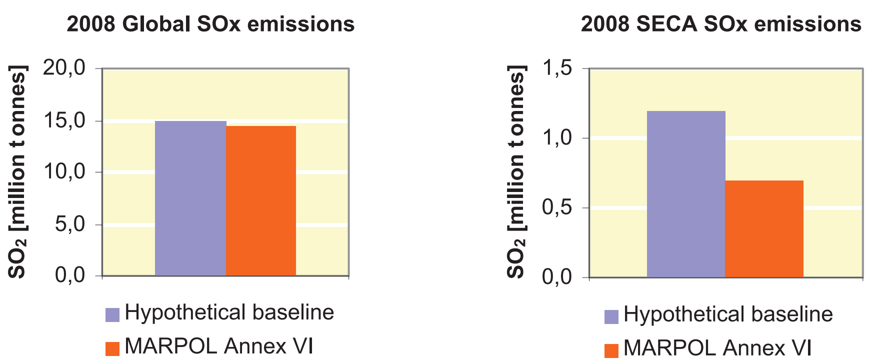


Figure 4.4 *Reductions of emissions of SO_x estimated for 2008*

REGULATION 15 – VOLATILE ORGANIC COMPOUNDS (VOCS)

4.18 Emissions of Volatile Organic Compounds (VOCs) are addressed in regulation 15 of MARPOL Annex VI. This regulation deals with how ports and terminals that are under the jurisdiction of parties to the Annex should regulate emissions of VOCs from tanker loading. In particular, where such regulations are employed, parties to Annex VI are to communicate such regulation of activity to IMO. By the end of 2008 no party had communicated the existence of such regulation to IMO [9], although several plants for the recovery of VOCs are in operation in various parts of the world, including the USA, Europe and Japan [10].

4.19 The most tangible result of regulation 15 is the introduction of standardized VOC return pipes that enable tankers to deliver VOC discharges to shore during loading. According to INTERTANKO, most tankers now have this equipment on board, although the frequency of use is variable but not common [10].

4.20 The updated Annex VI requires crude oil tankers to have and to use a VOC Management Plan. This is intended to focus the attention of crude oil tanker operators on the fugitive loss of VOCs during loading and transit, and to provide instructions for operators on how to operate their vessels in such a way as to minimize emissions.

REFERENCES

1 Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC), United Nations Environment Programme 1998 RTOC Assessment Report. http://ozone.unep.org/teap/Reports/RTOC/index.shtml

2 Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC), United Nations Environment Programme 2006 RTOC Assessment Report. http://ozone.unep.org/teap/Reports/RTOC/index.shtml

3 Resolution MEPC.176(58), adopted on 10 October 2008. "Amendments to the Annex of the Protocol of 1997 to amend the International Convention for the Prevention of Pollution from Ships, 1973, as modified by the Protocol of 1978 relating thereto".

4 "Interim guidelines for the application of the NO_x Technical Code". MEPC/Circ.344, issued 19 November 1998.

5. Marine Exhaust Emissions Programme (Main report, Steady State operation and Slow speed addendum) Lloyd's Register Engineering Services. 1995. Lloyd's Register House, 29 Wellesley Road, Croydon, CR0 2AJ, UK.

6 "Quantification of emissions from ships associated with ship movements between ports in the European Community". 2002. Report prepared by Entec UK Ltd for the European Commission. http://ec.europa.eu/environment/air/quality/background.htm#ansport

7 Resolution MEPC.82(43), adopted on 1 July 1999. "Guidelines for monitoring the world-wide average sulphur content of residual fuel oils supplied for use on board ships". http://www.imo.org/includes/blastDataOnly.asp/data_id%3D15684/82%2843%29.pdf

8 MARTOB: Onboard Treatment of Ballast Water (Technologies Development and Applications) and Application of Low-sulphur Marine Fuel, DTR-6.10-UNEW-07.04.

9 Information provided by IMO secretariat in March 2008.

10 Information provided by INTERTANKO in February 2009.

5

Technological and operational potential for reduction of emissions

5.1 As shown in Chapter 3, ships are a significant source of air pollution and emissions of greenhouse gases. Chapter 4 clearly demonstrates that it is possible to achieve reduction of emissions through international regulations. This chapter reviews potentials for reduction of emission of GHG and other relevant substances from a technological perspective.

5.2 In principle, there are four fundamental categories of options for reducing emissions from shipping.

1. Improving energy efficiency, i.e. doing more useful work with the same energy consumption. This applies to both the design and the operation of ships.
2. Using renewable energy sources, such as the wind and the sun.
3. Using fuels with less total fuel-cycle emissions per unit of work done, such as biofuels and natural gas.
4. Using emission-reduction technologies – i.e. achieving reduction of emissions through chemical conversion, capture and storage, and other options.

5.3 These options are discussed in the following sections. More detailed and complementary information on specific emission-reduction solutions and technologies is provided in Appendix 2 to this report.

OPTIONS FOR IMPROVING ENERGY EFFICIENCY

5.4 Improved energy efficiency means that the same amount of useful work is done, but using less energy. This in turn means less fuel burned and reductions in emissions of all exhaust gases. A wide range of options are available for increasing the energy efficiency of ship design and ship operation. Key areas of importance for energy saving are shown in Table 5.1, where options are categorized as "design" and "operation".

Table 5.1 *Principal options for improving energy efficiency*

DESIGN	OPERATION
Concept, design speed and capability	Fleet management, logistics and incentives
Hull and superstructure	Voyage optimization
Power and propulsion systems	Energy management

IMPROVING ENERGY EFFICIENCY BY SHIP DESIGN

5.5 Paragraphs 5.5 to 5.20 deal with options to improve the energy efficiency by changes in design. The development of the energy efficiency design index, EEDI, by MEPC (see Chapter 6) is an effort to exploit this option to increase efficiency. Most modifications of design are primarily suitable for newbuildings. This means that the phase-in and the reductions achieved by design-based improvements in energy efficiency will be slow, due to the long service life expected for ships (Chapter 2). Certain options may, however, be retrofitted to existing ships.

Concept, design speed and capability

5.6 The energy efficiency of a ship is closely linked to the specification of the original design. Speed, size, and key parameters such as beam, draught, and length have significant influence on the potential energy efficiency of the design. Restrictions on draught, beam, length, etc., imposed by requirements to access harbours and canals, constrain the design, with possible adverse effects on efficiency. Geared ships (i.e. ships with cranes to unload cargo) or ice-class ships and ships with redundant propulsion systems may be less energy-efficient; however, such ships also have extra capabilities [1].

5.7 Ships' lifetimes may exceed thirty years, and the operating and business environment may change significantly in the course of this time. Flexibility to allow upgrades and efficient operation in different scenarios should be considered at the design stage. It is thus critical to build the right ship for the job, which provides sufficient flexibility in operation. Specifying a ship and subsequently designing to that specification is a highly complex task. Estimating the potential for saving energy at this stage is equally complex; however, the influence of choices that are made at this stage of the design process is very significant and should not be under-estimated [2, 3]. For instance, while larger ships tend to be more efficient per tonne-mile than smaller ships when loaded, smaller or better-adapted ships may achieve a higher utilization factor, which may result in higher overall efficiency. The design speed also has a significant impact on transport efficiency.

5.8 The emission-reduction potential of concept, speed and capability is closely linked to the ship's operations. Better planning at the design stage may lead to a higher potential for reduction at the operational stage.

Hull and superstructure

5.9 Optimization of the underwater hull form is regularly applied to new ship designs. It is likely that most new designs today are going through some systematic form of hull optimization process, focusing on reduced resistance and improved propulsive efficiency. The actual proportion of the world fleet that has undergone this process is not known. Such optimization is challenging, and it is difficult to ensure that the final result from the "optimization" procedures performed really does provide an optimum design as the end result. Ensuring optimal working conditions for the propeller is a key issue in hull optimization, and hull and propeller optimization is done as a single process.

5.10 A key issue is that the design point for optimization should be as relevant as possible to the operation of the ship. In particular, full optimization for weather and waves is not always achieved. This may be linked, in part, to the fact that the trial runs, on which the performance of the ship is measured with respect to the contracted performance, are performed under still-water conditions.

5.11 The superstructure of the hull represents a small fraction of the resistance; however, it is still possible to save energy by optimizing the design so as to minimize air resistance and the adverse effects of side winds, such as drifting. This is particularly important for ships with large superstructures.

5.12 Reducing the weight of the hull reduces the wetted surface area and the drag at any given payload, thus saving energy. The potential for reducing weight is linked to strength and safety requirements and how they are specified in design codes. To reduce weight, it will generally be necessary to use high-grade steels and lighter materials. At present, lightweight materials such as aluminium, carbon fibre or glass-fibre sandwich constructions are mainly used on planning high-speed craft.

5.13 The first greenhouse gas study [4] analysed model tests from MARINTEK's database in order to estimate the potential for optimization. This analysis indicated a potential for savings in the range 5–20% for optimization of the behaviour of the hull in still water. The potential for savings may be greater for smaller ships, where there are less resources for optimization and ships are built in smaller series. Optimization of the hull must also consider its performance in waves, which has also been shown to differ significantly between ships [5].

Power and propulsion systems

5.14 Power on board is generated either by low-speed or medium-speed diesel engines, except in very special cases. Energy efficiency in the power-generation system can be increased in many ways.

5.15 The efficiency of older engines can be improved through upgrading (modernizing) engines and replacing old turbochargers or by de-rating engines, if lower power can be accepted. This type of upgrade is not very common at present, probably due to the cost and complexity. The upgrade of the engine may also be considered to be a major modification, in which case it will be necessary to obtain and maintain a new certificate with respect to IMO NO_x regulations.

5.16 Energy can be recovered from exhaust gases by using power turbines, driven either directly by an exhaust side-stream, by steam generated from the waste heat from the engine, or by both methods. The power that is recovered can then be used to drive a shaft generator/motor to generate electricity or to assist the main engine. Energy may also be recovered from the exhaust gases from auxiliary engines. Future systems may see the use of fluids other than steam, since these may permit smaller systems with higher efficiencies. Recovery of energy from exhausts can generate additional power corresponding to about 10% of the total, and shaft efficiencies can be increased from 50% to about 55% for large two-stroke engines. Recovery of energy from exhausts can also be used on smaller engines. Two-stage turbocharging can be considered as another means of capturing exhaust energy to increase energy efficiency [5].

5.17 In cases where the operating profile is variable, special arrangements may be installed to optimize utilization and efficiency, e.g., "father and son" propulsion engine arrangements, variations in number and size of auxiliary engines, shaft generator systems, etc. Diesel-electric propulsion systems may also be considered for energy-saving purposes in these cases; however, electric propulsion introduces additional transmission losses that must first be recovered before any saving can be made. Diesel-electric propulsion provides other benefits, such as increased design flexibility, which may indirectly translate to energy saving.

5.18 Thrust is generated in the propeller where high propeller efficiency is obtained with a large propeller rotating at low speed. Ideally, the number of blades should be minimized, to reduce blade area and frictional resistance. Typical design restrictions are limitations on diameter, cavitation and loading. The size of the propeller may be limited by the design of the ship, by restrictions on draught in expected areas of operation or by engine torque [1].

5.19 In certain cases, energy efficiency can be gained through various enhancements such as vanes, fins, ducts, high-efficiency rudders, vane wheels, asymmetric rudders, contra-rotating propellers, etc. A number of such devices are described in Appendix 2. Many of these devices can be considered generically as alternative ways of recovering rotational energy of the propeller. The typical potential savings of such systems are assessed to be in the order of 5–10% of the ship propulsion power, although higher figures may be presented by industry for specific cases.

5.20 Not all of these propulsive devices are suitable for all kinds of ships. Special propulsion-enhancing devices are not widely used, due to cost, reliability issues, etc. The mechanical loading on the propeller is very high and the ability to withstand heavy seas is critical. Moreover, it is difficult to measure the benefits of such devices in full scale, and the benefits that are achieved in one ship may not be transferable to another. Therefore, investing in such advanced propulsion devices may be regarded as being rather risky.

ENERGY SAVING BY OPERATIONS

5.21 Saving energy at the operational stage can be achieved by all ships. However, as discussed in paragraphs 5.6 to 5.8, new ships may have more flexibility to exploit potential operational improvements, e.g., such as better cargo-handling gear, ability to cruise efficiently at different speeds, etc. Saving energy at the operational stage is presently addressed by the MEPC with the development of the Energy Efficiency Operational Indicator (EEOI) and the Ship Efficiency Management Plan (SEMP).

Fleet management, logistics and incentives

5.22 Energy efficiency can be improved by using the right ships in a transport system. Generally speaking, efficiency will increase if we concentrate cargoes in larger ships wherever possible, as demonstrated in paragraphs 5.6 to 5.8. While using large ships tends to reduce energy consumption in the shipping leg itself, the total impact on overall door-to-door logistics performance may be negative unless such a move is complemented by smaller ships that can assist in the onward distribution of cargoes. Naturally, larger ships are not efficient if not enough cargo is available and they have to sail only partly loaded. Net energy efficiency may be better for a small ship, with access to more ports and cargo types, being able to fill its cargo hold to capacity [7].

5.23 Reductions in scheduled speed (i.e. accepting longer voyage times) will increase efficiency, but result in more ships being needed. Reductions in scheduled speed can be expensive, since they directly affect the amount of freight carried and hence the income of a ship. However, there is a trade-off between freight rates and fuel cost: when freight rates are low and fuel prices are high, it may be profitable to reduce speed.

5.24 Traffic management and control systems, including queue prioritization on criteria other than “first in”, may also play a role. Reducing time in port through more efficient cargo handling, berthing and mooring can also help to reduce emissions.

5.25 While there may be many opportunities to optimize and improve operational efficiency at some level (e.g., as discussed in paragraphs above and in paragraphs 5.29 to 5.38 as well as the description of the SEMP [30]), doing so requires the cooperation of several parties. It is essential that each of these has the incentives and flexibility to join the energy-saving effort, and it is particularly important that they do not have incentives to contribute to inefficient behaviour. As an example of the latter, ship upgrades and major maintenance activities depend on the high-level strategies of the operating companies. In cases where ships are operated by a different company than the commercial operator, the technical operator may tend to minimize time in dry dock (to minimize off-hire cost) and other maintenance costs (e.g., painting costs) while at the same time handing the fuel bill to the commercial operator. In another example, a ship operator may arrive in a busy harbour, only to wait for days or weeks to unload, while receiving compensation (demurrage) for each day of waiting. It is evident that contractual arrangements and incentives have a significant influence on operations and hence on efficiency.

5.26 Typically, contracts are agreed between two parties only, and aim to safeguard the (economic) interest of the parties under various conditions. In the typical time charterparty the charterer both controls the speed and the fuel bill, as well as the consequences of delay. Under a typical voyage charterparty the ship operator sets the speed, but is also entitled to an economic compensation – demurrage – in case of a delay in port due to congestion. If the port is able to handle the ship, the ship operator can take on a new cargo; if not, the ship operator is compensated by the demurrage. Often the demurrage rate is higher than the extra fuel cost and then, in both cases, the incentive for the ship operator is to sail at high speed to arrive as early as possible.

5.27 The net result may be low flexibility for efficient operation and, in the worst cases, incentives for inefficient operation. While it is easy to point to areas where the present system falls short, it is more difficult to find solutions that would resolve these issues to the satisfaction of all parties. Indeed, there are many parties involved in shipping that directly or indirectly affect transport efficiency. The relationship between these actors is regulated by a number of contracts. Depending on the type of shipping, the list of involved parties may include:

- owner (including bareboat charterer/operator);
- charterer;
- multi-modal transport operators (MTOs);
- shipper and receiver of the goods;
- cargo buyer/seller (the original source of the transport demand);
- transport agents/brokers;
- port authorities; and
- terminal operators.

5.28 Transport efficiency is affected by time spent in port: additional to the parties listed above, other parties (including shipping agents, stevedores, tug operators, pilots, bunker suppliers and other service providers) may have a role to play in minimizing port time.

Voyage optimization

5.29 Voyage optimization is the optimization of ship operation that the master can achieve within the constraints that are imposed by logistics, scheduling, contractual arrangements and other constraints. These include issues such as:

- Selection of optimal routes with respect to weather and currents in order to minimize energy consumption (weather routeing);
- Just-in-time arrival, considering tides, queues, and arrival windows. As discussed above, incentives and contractual arrangements are very important in this respect. For instance, severe penalties for late arrival encourage safety margins on the ship side. Extra payment for time spent waiting (demurrage) discourages just-in-time arrival;
- Ballast optimization – avoiding unnecessary ballast. Determining optimal ballast is sometimes a difficult consideration, as it also affects the comfort and safety of the crew; and
- Trim optimization – finding and operating at the correct trim.

5.30 The potential improvements in efficiency that can be gained by voyage optimization are highly variable and difficult to assess on a general basis, since this depends on how ships are presently operated. In the 2000 study of greenhouse gas emissions from ships, the fleet average potential saving by optimization of trim and ballast in operation was estimated as small (0–1% of total fuel consumption) [4]. In a recent specific case study of tanker operations done by DNV, savings of 0.6% were estimated for trim and ballast optimization. Higher figures may be relevant for specific ship types that carry significant ballast during much of the operation.

5.31 Weather routeing can result in substantial savings for ships on certain routes. However, weather routeing systems are not uncommon, and the incremental saving that can be expected from improvements in such systems and from their more widespread use has not been assessed. The potential for just-in-time arrival was assessed at 1–5% in the 2000 study [4]. The highest potential saving would be expected where economic considerations (incentives from contractual arrangement) presently favour inefficient operational arrival. More recently, the potential for energy saving by just-in-time arrival has been estimated to be 1% [32], based on the Japanese domestic fleet.

5.32 Several types of weather routeing systems, technical support systems, performance monitoring systems and other systems can be used to help achieve optimal voyage performance. These systems must be used and understood, and the skills and motivation of the crew are critical. Incentive schemes, whereby crew members profit from efficient operation, are one approach to improving motivation.

Energy management

5.33 Besides the power needed for propulsion, electric power is needed to sustain the crew (the hotel load) as well as various ancillary systems, such as cooling-water pumps, ventilation fans, control and navigational systems, etc. Most merchant ships have transverse thrusters, for manoeuvring at low speed, which need significant power but are used only for short periods. Some ships also carry cargo gear that requires high power when loading and unloading. Passenger ferries and cruise ships will have significant power demands for passenger accommodation, ventilation and air-conditioning. Significant heat demands may also be required for passenger comfort and for production of fresh water.

5.34 In certain cases, the cargo requires cooling to maintain quality; e.g., refrigerated or frozen cargo. Certain cargoes, such as special crude oils, heavy fuel oils, bitumen, etc., require heating. Some of this heat can be supplied by generating steam, using heat from the exhaust. However, in many cases an additional steam boiler is needed to supply sufficient steam. Steam from exhaust gas is generally sufficient to heat the heavy fuel oil that is used on most ships; in port, however, steam from an auxiliary boiler may be needed.

5.35 It is often possible to reduce energy consumption on board by working towards more conscious and optimal operation of ship systems. Examples of measures that can be taken include:

- avoidance of unnecessary consumption of energy;
- avoidance of parallel operation of electrical generators;
- optimization of steam plant (tankers);
- optimization of the fuel clarifier/separator;
- optimized HVAC operation on board;
- cleaning the economiser and other heat exchangers; and
- detection and repair of leaking steam and compressed-air systems, etc.

5.36 This may require investments in training and motivating the crew, and in monitoring/benchmarking consumption. In parallel, upgrades of automation and process control, such as automatic temperature control, flow control (automatic speed control of pumps and fans), automatic lights, etc., may help to save energy. The energy-saving potential of energy-management measures is difficult to assess, as this depends on how efficiently the vessel was already being operated and on the share of auxiliary power consumption in the total energy picture. A saving of 10% on auxiliary power may be realistic for many vessels. This corresponds to ~1–2% of total fuel consumption, depending on circumstances.

5.37 Optimal maintenance of main engines and ensuring that these are operating at the most effective (highest) pressures is also important. Savings of 1–2% of the fuel consumption of the main engine through "tuning" have been observed, with even more in extreme cases, although the average potential may be around 1%.

5.38 Maintaining a clean hull and propeller is important for fuel efficiency. Many shipowners have made substantial savings by increasing the frequency of cleaning operations on the hull and propellers or by implementing condition-based cleaning. Selection of more effective hull coatings may reduce resistance and result in longer intervals between dry-dockings. Surface finishing, hull coating and friction reduction are all very important in determining resistance. As discussed in appendix 1, the appropriate choice of hull coating and hull maintenance alone can amount to a 5% difference in energy requirements.

RENEWABLE ENERGY SOURCES

5.39 Renewable energy can be used either directly on board ships (by utilizing wind, solar and wave energy) or energy can be generated on-shore and converted into an energy carrier such as hydrogen or electricity.

WIND POWER, ON BOARD USE

5.40 Wind power can be exploited in various ways as the motive power for ships, for example by:

- traditional sails;
- solid wing sails;
- kites; and
- Flettner-type rotors.

5.41 These systems have different characteristics. Wind conditions differ between regions, so that wind power is more attractive in certain regions and routes than in others. In a study carried out at the Technical University of Berlin [8], three different types of sail were modelled on two types of ships on three different routes. The objective of the study was to assess the potential savings of energy and of fuel obtainable over a five-year period, using actual weather data. This study indicated that the potential for sail energy was better in the North Atlantic and North Pacific than in the South Pacific. Fuel savings were slightly greater at higher speeds. However, in terms of percentages, the fuel savings were greater at low speed, due to the low total demand for propulsion power. In percentage terms, savings were typically about 5% at 15 knots, rising to about 20% at 10 knots.

5.42 Present-day experience of all of these technologies on board large vessels is limited, and modelling results are therefore difficult to verify. Nevertheless, wind-assisted power appears to have potential for fuel-saving in the medium and long term.

SOLAR POWER, ON BOARD USE

5.43 Current solar-cell technology is sufficient to meet only a fraction of the auxiliary power requirements of a tanker, even if the entire deck area were to be covered with photovoltaic cells. Naturally, at certain times and in certain areas, solar radiation will be above average and the auxiliary demands for power could be met. Moreover, since solar power is not always available (e.g., at night), backup power would be needed. Therefore, solar power appears to be of interest primarily as a complementary source of energy. With present technology it could be possible to save only a few percent of total energy requirements, even with extensive use of solar power. However, present-day cost levels and efficiency place solar power towards the lower end of the cost-effectiveness list [9].

WAVE POWER, ON BOARD USE

5.44 This includes concepts for utilizing wave energy and/or ship motion. Examples include internal systems (gyro-based) and external systems such as wavefoils, stern flaps or relative movement between multiple hulls (trimarans). These systems have high technical complexity, limited potential energy efficiency and are not regarded as being very promising.

RENEWABLE ENERGY FROM SHORE

5.45 Renewable energy is generated onshore from wind turbines, hydroelectric schemes, geothermal plants, solar energy plants, etc. Potentially, energy from such sources could be used to power ships if a suitable energy carrier was available. However, as long as there is a shortage of renewable energy onshore, there is little to be gained by directing shore-based renewable energy to ship propulsion. A notable exception is the use of shore power when a ship is berthed.

FUELS WITH LOWER FUEL-CYCLE CO_2 EMISSIONS

5.46 Emissions of CO_2 can be cut by switching to fuels with lower total emissions through the full fuel cycle (i.e. production, refining, distribution and consumption). The switch from using residual fuels to distillate fuels that is implied by the sulphur regulation in the revised MARPOL Annex VI has already been agreed; hence, there is no reason to discuss the potential merits and demerits of this move on the emission of CO_2 here. Other fuel options with potential benefits for reducing the production of CO_2 include biofuels and natural gas.

BIOFUELS

5.47 Present-day biofuels (often referred to as "first-generation" biofuels) are produced from sugar, starch, vegetable oil, or animal fats. Many of these fuels can readily be used for ship diesels with no (or minor) adaptation of the engine. Depending on source, there are certain technical issues, such as stability during storage, acidity, lack of water-shedding (potentially resulting in increased biological growth in the fuel tank), plugging of filters, formation of waxes, increased engine deposits, etc., which suggest that care must be exercised in selecting the fuel and adapting the engine. Care must be exercised to avoid contamination with water, since biofuels are particularly susceptible to biofouling. Blending bio-derived fuel fractions into diesel fuel or heavy fuel oil is also feasible from the technical perspective; however, compatibility must be checked, as with bunker fuels [25, 26, 27]. It should be noted that, although many of the technical challenges related to biofuels may look trivial, the consequence may be engine shutdown, which may be more critical with respect to the safety of a ship than, for instance, in the case of a car or a stationary combustion source on land. First-generation biofuels can be upgraded (hydrogenated) in a refinery. In this case, the resulting fuel is of high quality and the aforementioned practical problems do not apply. This upgrading costs energy, and hence results in additional emissions.

5.48 The net benefits on emissions of CO_2 differ among different types of biofuels. Not all biofuels have a CO_2 benefit [25, 28]. The benefit is related to how the fuel is produced; hence the CO_2 benefit is not necessarily a function of the type of fuel alone. Biofuels have different combustion characteristics than traditional diesel. Use of biofuels has in certain cases resulted in a 7% to 10% increase in the NO_x emissions; however, the effect of NO_x could be different if the engine was optimized (e.g., fuel injection rate and timing) for biofuel in these cases.

5.49 First-generation biofuels have been criticized for diverting food away from the human food chain, leading to food shortages and higher prices. Additional issues relate to deforestation, soil erosion, impact on water resources and more. Sustainability issues related to biofuels are discussed in the UN-Energy paper "Sustainable Biofuels: a framework for decision makers" [29].

5.50 Biofuel produced from residual non-food crops, non-food parts of current crops (leaves, stems), and also industry waste such as wood chips, skins and pulp from fruit pressing is sometimes referred to as "second-generation" biofuels. These fuels are considered more sustainable. The conversion process that is needed to facilitate production of second-generation biofuel on an industrial scale and economically viable is still in development. Biofuels based on using algae are sometimes referred to as "third-generation" biofuels. This technology is presently at an early stage of development.

5.51 In summary, the present potential for reducing emissions of CO_2 from shipping through the use of biofuels is limited. This is caused not only by technology issues but by cost, by lack of availability and by other factors related to the production of biofuels and their use. Additionally, the biofuels are, at present, significantly more expensive than petroleum fuels. Possible future use of biofuels towards 2050 is discussed in Chapter 7 within the context of IPCC scenarios.

LIQUEFIED NATURAL GAS (LNG)

5.52 Liquefied natural gas can be used as an alternative fuel in the shipping industry. The fuel has a higher hydrogen-to-carbon ratio compared with oil-based fuels, which results in lower specific CO_2 emissions (kg of CO_2/kg of fuel). In addition, LNG is a clean fuel, containing no sulphur; this eliminates the SO_x emissions and almost eliminates the emissions of particulate matter. Additionally, the NO_x emissions are reduced by up to 90% due to reduced peak temperatures in the combustion process. Unfortunately, the use of LNG will increase the emissions of methane (CH_4), hence reducing the net global warming benefit from 25% to about 15% [24].

5.53 LNG-propelled ships will be particularly attractive in future emission control areas since they can meet Tier III emission levels and the SO_x requirements without any treatment of the exhaust gas.

5.54 One of the main challenges for the use of LNG as a fuel for ships is to find sufficient space for the on board storage of the fuel. At the same energy content, LNG has a volume 1.8-times larger than diesel oil. However, the bulky pressure storage tank requires a large space, and the actual volume requirement is in the range of three times that of diesel oil. In addition, the availability of LNG fuels in bunkering ports is a challenge which needs to be solved before LNG becomes a practical alternative. Conversion from diesel propulsion to LNG propulsion is possible, but the LNG is mainly relevant for newbuildings since substantial modification of engines and allocation of extra storage capacity is required.

5.55 At present, the LNG technology is only available for four-stroke engines. For two-stroke engines, a different gas-engine concept, based on direct injection, may be more attractive. The NO_x benefit of this technology is less than the premixed lean-burn concept that is used in four-stroke engines.

5.56 In summary, the present potential for reduction of emissions of CO_2 from ships through the use of LNG is somewhat limited, since it is mainly relevant for newbuildings and because, at present, LNG bunkering options are limited. The forthcoming NO_x and SO_x ECAs will provide significant additional incentives for the use of LNG propulsion in short sea operations, since ECA requirements can easily be met by LNG-propelled ships. The price of LNG is presently significantly lower than that of distillate fuels, making an economic incentive for a move to LNG.

EMISSION-REDUCTION TECHNOLOGIES

5.57 Various emission-reduction technologies are available. Although it is possible to remove CO_2 from exhaust gases, e.g., by chemical conversion, this is not considered feasible. Indeed, considering the list of pollutants in the scope of this report, emission-reduction technologies are mainly relevant to pollutants within exhaust gases, i.e. NO_x, SO_x, PM, CH_4, NMVOC. Technological options for reducing these emissions are discussed in Appendix 2, and only a brief introduction is given here.

EMISSION-REDUCTION OPTIONS FOR NO_X

5.58 Emissions of NO_x from diesel engines can be reduced by a number of measures, including:

- fuel modification, e.g., water emulsion;
- modification of the charge air, e.g., humidification and exhaust gas recirculation (EGR);
- modification of the combustion process, e.g., miller timing; and
- treatment of the exhaust gas, e.g., selective catalytic reduction (SCR).

5.59 The sulphur content and the deposit-forming tendency of a fuel influence the possibilities for other emission-reduction technologies, such as exhaust gas recirculation (EGR) or selective catalytic reduction (SCR). Consumption and purity of water are issues with all options that use water.

5.60 A certain trade-off exists, as the emissions of CO_2 and of PM increase when those of NO_x are reduced. This does not mean that future engines, with lower NO_x levels, must have higher levels of CO_2, HC, CO and PM emissions than current models. Simultaneous improvement in several areas is possible, as demonstrated in [5]. What remains is that, if the improved engine was re-optimized, NO_x could still be traded against other pollutants. Miller cycling, in combination with two-stage turbocharging, has resulted in reductions in NO_x emissions of >40% and improved fuel consumption in four-stroke engines [5].

5.61 The use of LNG as a fuel is both a switch of fuel and a change in the combustion process. LNG operation can bring about very large reductions in NO_x emissions (~90%) in four-stroke engines [10]. The potential for reduction of NO_x emissions for large two-stroke engines has not been demonstrated. Use of LNG as a fuel is discussed in paragraphs 5.52 to 5.56.

5.62 Tier II NO_x limits, i.e. 15–20% reduction from the current levels, can be achieved with modifications of the internal-combustion process. At present, reduction of emissions of NO_x to Tier III limits (~80% reduction from Tier I) can only be achieved by selective catalytic reduction (SCR) post-treatment or by using LNG and lean premixed combustion. These technologies are proven for four-stroke engines; however, experience with large two-stroke engines is limited.

5.63 By using SCR and LNG technology, it is possible to achieve reductions of emissions even beyond Tier III limits on some load points. However, achieving further reductions at low load is problematic with SCR, principally because the temperature of exhaust gases from marine engines is not sufficiently high for effective operation of the catalyst. Achieving reduction of emissions to a very low level consistently, for extended time periods, may prove problematic with a catalyst, due to its possible deactivation. Technology for reduction of NO_x emissions at low load in marine engines is presently being forced by IMO through the modified Tier III test-cycle requirements in the revised NO_x Technical Code.

EMISSION-REDUCTION OPTIONS FOR SO_X

5.64 Emissions of SO_x originate in sulphur that is chemically bound to the fuel hydrocarbon. When the fuel is burned, the sulphur is oxidized to SO_x (mainly SO_2). In order to reduce SO_x emissions, it is necessary to use a fuel with lower sulphur content or to remove the SO_x that is formed in the combustion process.

5.65 The revised MARPOL ensures that significant reductions of SO_x emissions will be achieved through limitations on the sulphur content of fuel. As an alternative to using low-sulphur fuels, an exhaust-gas scrubbing system can be employed to reduce the level of sulphur dioxide (SO_2). Two main principles exist: open-loop seawater scrubbers and closed-loop scrubbers. Both scrubber concepts may also remove PM and limited amounts of NO_x [16, 17]. Scrubbing of exhaust gases requires energy, which is estimated to be in the range of 1–2% of the MCR [18].

5.66 Scrubbing to remove SO_x reduces the temperature of exhaust gas. On the other hand, SCR technology requires high temperatures of exhaust gas and at the same time creates low sulphur and PM content in the exhaust gas. Combining SCR with scrubbing to remove SO_x is thus not considered feasible.

5.67 Pollutant material that is removed from the exhaust is carried in the wash water. Sulphur oxides react with the seawater to form stable compounds that are normally abundant in seawater and not believed to pose a danger to the environment in most areas. On the other hand, particulate matter in the exhaust that is trapped in the seawater may be harmful to the environment. The revised IMO Scrubber Guidelines [31] provide limits for the effluent, including limits for Polycyclic Aromatic Hydrocarbons (PAH), turbidity, pH, nitrates and other substances. Port State requirements for effluent discharges will have a significant impact on the possible use of seawater scrubbers. To fulfil these requirements, it will be necessary to install a treatment system to clean the effluent. Generally, the more SO_x and PM that is removed from the exhaust by the scrubber, the more pollutant will have to be removed from the effluent.

EMISSION-REDUCTION OPTIONS FOR PM

5.68 Unlike other emissions, which are chemically defined, particulate matter (PM) is defined in international standards (ISO 8178) as the mass that is collected on a filter under specified conditions. However, the mass of PM does not define the chemical composition and the size distribution of the PM; these are important to health and in causing environmental effects.

5.69 The extent of generation of Particulate Organic Matter (POM) is related to the consumption of engine lubricating oil, which may potentially be reduced. Changes in the base stocks and the additives of lube oil may also reduce PM mass. Emissions of elemental carbon are related to the amount of soot that is formed during combustion, some of which may be removed. Amounts of organic material and of elemental carbon that are generated may therefore be considered to be fuel-independent. Amounts of sulphate, associated water and ash are mainly determined by the fuel. When the sulphur content of a fuel is high, the PM emissions are mainly fuel-dependent, while other PM fractions are comparatively insignificant. When the sulphur content of a fuel is reduced, fuel-independent PM is less prominent.

5.70 Some emissions of PM from high-sulphur fuels can be reduced by scrubbing with seawater. Claims for the potential reduction of PM levels range from 90% to 20%, depending on source [16, 17]. With low-sulphur fuels, emissions of PM can be further reduced by optimizing combustion to achieve increased oxidation of soot and of PM, minimizing consumption of lube oil and minimizing the use of additives in lube oil. The burning of fuel–water emulsions can also reduce emissions of PM to a certain extent.

5.71 Post-treatment technologies that have been considered or are used in the automotive sector, such as particulate traps, are not regarded as being suitable for marine fuels due to the high sulphur content in these fuels [18]. Even future levels of 0.1% of sulphur in the fuels that are used in a SECA are 100-times the current sulphur limit for automotive diesel that is used in the European Union.

EMISSION-REDUCTION OPTIONS FOR CH_4 AND NMVOC

5.72 Engine exhaust emissions of methane (CH_4) and NMVOC are comparatively low. Some reductions may be achieved by optimizing the combustion process. NMVOC may also be oxidized with a catalyst. Oxidation catalysts are not uncommon in conjunction with SCR installations, where they oxidize unused ammonia, thus eliminating emissions of ammonia. Levels of CH_4 in exhaust are more difficult to reduce by using a catalyst.

5.73 Emissions of CH_4 from gas engines are due to unburned methane arising from the process of premixed combustion. The level of CH_4 emissions depends on the layout of the combustion chamber. By careful design to avoid crevices, emissions can be significantly reduced. However, there will be a remaining level of CH_4 emissions. This CH_4 can be oxidized by using a catalyst, although this is not as simple as reducing the levels of NMVOC, and this is an area for research and development.

5.74 Emissions of CH_4 from gas engines can be virtually eliminated by replacing the concept of lean premixed combustion with high-pressure gas injection. This latter concept is believed to be beneficial for large two-stroke engines. The disadvantage of this option is that the reduction of NO_x emissions that is achieved through direct injection is less than can be achieved with lean premixed combustion.

OPTIONS FOR REDUCING EMISSIONS OF HFC AND OTHER REFRIGERANTS

5.75 Emissions of HFC are related to leaks during the operation and maintenance of refrigeration plants. Technical measures to reduce leaks include designs that are more resistant to corrosion, vibration and other stresses, reducing the impact of leaks by reducing the refrigerant charge (i.e. by indirect cooling), and compartmentalizing the piping system, so that a leakage may be isolated. It is also important that facilities are available to allow safe and not unreasonably burdensome recovery of refrigerants during maintenance. Operational measures include planned maintenance and monitoring of the consumption of refrigerant in order to prevent and detect leaks [19, 20].

ASSESSMENT OF POTENTIAL REDUCTION OF EMISSIONS

POTENTIAL FOR REDUCTION OF CO_2 EMISSIONS

5.76 A number of options for improvements in efficiency have been discussed in previous paragraphs and the potential for saving energy by combining these options is very significant. On the other hand, costs, lack of incentives and other barriers prevent many of them from being adopted. Therefore, when making an assessment of the potential saving, we also make implicit assumptions regarding the degree of compromise, effort and extra costs that would be required. An assessment of energy-saving potentials, using known technology and practices, is shown in Table 5.2. The ranges in the figures in this table express the variation in potential for different ship types and the degree of commitment to making savings.

5.77 Assumptions of future improvements in efficiency are used in the future emissions scenarios presented in Chapter 7. The high figures shown in Table 5.2 correspond fairly well to the scenario with the highest improvement in energy consumption, in which net improvements, excluding the use of low-carbon fuels, range from 58% to 75% in 2050 depending on the ship type. This assumption, as well as indicators of historic transport efficiency for different ship types, is illustrated in Figure 5.1. The background of the generation of historical efficiency data is presented in Chapter 9.

Table 5.2 *Assessment of potential reduction of CO_2 emissions from shipping by using known technology and practices*

DESIGN (New ships)	**Saving (%) of CO_2/tonne-mile**	**Combined**	**Combined**
Concept, speed and capability	2–50†		
Hull and superstructure	2–20		
Power and propulsion systems	5–15	10–50%†	
Low-carbon fuels	5–15*		
Renewable energy	1–10		
Exhaust gas CO_2 reduction	0		25–75%†
OPERATION (All ships)			
Fleet management, logistics and incentives	5–50†		
Voyage optimization	1–10	10–50%†	
Energy management	1–10		

* CO_2 equivalent based on the use of LNG.
† Reductions at this level would require reductions of speed.

5.78 Another perspective on the potential for reduction is that of marginal abatement cost curves (MACC). These add information to the reduction potential, as given in Table 5.2, by also assessing the costs of measures. A MACC plots the maximum achievable reductions against estimated cost-effectiveness. Assuming that the most cost-effective measures for reduction of emissions are implemented first, the subsequent options will be more expensive and less effective. For example, if an improved design of hull reduces the energy requirement by 5% and a better propeller achieves a reduction of 3%, implementing both will not necessarily yield a reduction of 8%. A MACC always considers the cost of reducing the emissions by the next tonne of CO_2, given the reduction that has been achieved by the options that have already been implemented [22].

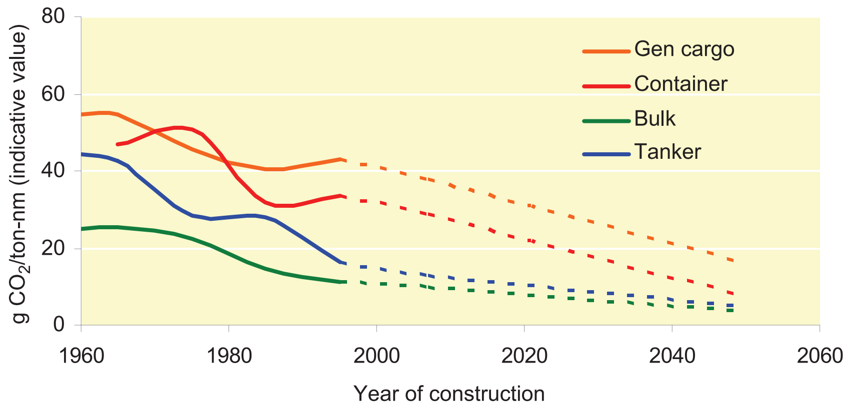


Figure 5.1 *Indicated historical efficiency and "high-efficiency" scenarios*

5.79 A MACC can inform policymakers about the costs of meeting certain reductions in emissions or the environmental effect of a tax or levy. It has to be noted, however, that the MACC does not capture all of the possible reactions to a certain policy. The effects of change of demand are absent, for example, so a thorough analysis of the costs of a policy should also use economic models.

5.80 The generation of MACC curves is very demanding in terms of data. This is especially true for the MACC that is presented here, as little data on the cost-effectiveness of emission-reduction measures in shipping was available hitherto. In this study, only a subset of measures (a total of 25 individual measures) was available for inclusion. In certain cases, the criterion for exclusion has been the availability of data rather than the relevance of those data. Nevertheless, sufficient options are included to provide a meaningful indication of costs and the reduction potential for the world fleet. A better coverage of measures would show that the potential to reduce emissions is larger. As some of the measures that have not been considered here are currently implemented, it seems reasonable to assume that the cost-effective potential to reduce emissions would also be larger.

5.81 Since, for most options, it is not possible to estimate a single value for costs and the potential for abatement, we decided to present ranges rather than single values. Assumptions, data and further information on the cost-effectiveness of specific measures are provided in Appendix 4. The marginal abatement cost curve for CO_2 is shown in Figure 5.2. In considering this curve, the following should be noted.

1. The curve adopts a social perspective. In other words, it answers the question of what it would cost the world economy to reduce emissions. It does not represent the expenditures that ship operators would have to make to do this.

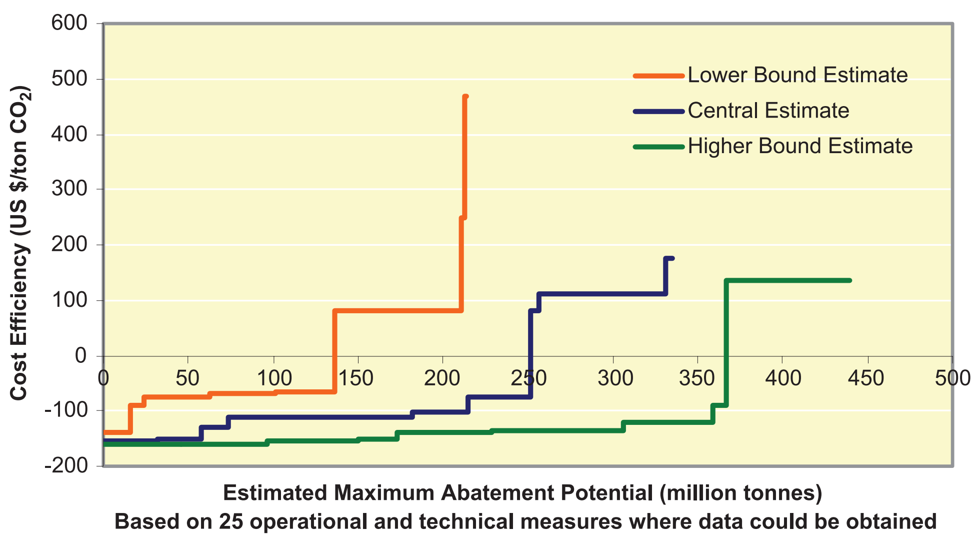


Figure 5.2 *Indicative marginal CO_2 abatement costs for 2020 (fuel price 500 $/tonne)*

2. The model assesses the fleet-average potential for abatement and the cost-effectiveness of measures. Some measures may be very cost-effective for some ship types, but would have high costs if applied to the world fleet. In that case, they would not seem to be cost-effective in this graph.
3. The model uses a subset of improvement options. The inclusion of more options would increase the total potential for reduction.
4. The maximum abatement potential is what can be implemented in the world fleet in 2020. It is not directly comparable to Table 5.2. Moreover, market constraints, such as limited availability of certain measures, have not been taken into account.
5. Some options have negative cost and would be profitable to use. There may be non-financial barriers that prevent their use, or they might be cost-effective from a social perspective but not from the perspective of a ship operator.
6. In general, higher discount rates will increase the investment annuity costs and shift the curve upwards (measures become less cost-effective).
7. In general, higher fuel prices increase the benefits of measures in terms of the fuel that is saved, and this shifts the curve downwards (measures become more cost-effective).
8. In 2020 the maximum abatement potential ranges from about 210 to 440 Mt of CO_2, i.e. about 15–30% of projected emissions in the A1 scenario family.

POTENTIAL FOR REDUCTION OF OTHER GHG EMISSIONS

5.82 A detailed analysis of impacts of emissions from shipping on climate is provided in Chapter 8. Somewhat simplified, the relative importance of the individual greenhouse gases that are emitted from ships can be indicated in terms of their global warming potential (GWP) [21]. A comparison of the GWP on a 100-year horizon, based on 2007, is shown in Table 5.3. This table shows that CO_2 is the primary GHG emitted by shipping, and that the potential for reduction of emissions from other sources is comparatively small.

Table 5.3 *Relative importance of GHG emissions from ships in 2007*

	million tonnes	GWP	CO_2 equivalent	GWP %
CO_2	1,050	1	1,050	98%
CH_4	0.24	25	6	0.6%
N_2O	0.03	298	8	0.7%
HFC*	0.0004	1,300	0.5	0.6%
SF_6	0	23,900	0	0
PFCs	Negligible	6,500–9,200	Negligible	Negligible

* The GWP values vary greatly between the different HFCs. The refrigerant HCFC-22 is the most commonly used refrigerant on board ships; hence the corresponding value of GWP is used in the above calculations.

5.83 The N_2O and the CH_4 fraction of the exhaust gas can be reduced in proportion to energy consumption. The reduction potentials indicated in Table 5.2 can thus be applied also to these emissions. Note that some emissions of CH_4 also originate in the transport and handling of crude oil, and that these emissions are not reduced by increasing ship efficiency. With respect to HFC, these emissions are leaks. The theoretical potential to reduce their emissions is thus very high, although it may be very difficult to achieve.

POTENTIAL FOR REDUCTION OF OTHER RELEVANT SUBSTANCES

5.84 Emissions of other relevant substances (NO_x, SO_x, PM, CO and NMVOC) in exhaust gases will be reduced as the energy efficiency of shipping increases. Therefore, the potentials that are indicated in Table 5.2 can be applied for these emissions also, although the fraction of emissions of NMVOC that originates in the transport and handling of crude oil is not affected. Paragraphs 5.84 to 5.90 discuss the potential for additional reductions.

5.85 The reductions in emissions that are mandated or expected from the revised Annex VI are shown in Table 5.4. The potentials for reduction are based on a sulphur content of 2.7% in fuel and PM compositions as shown in paragraphs 7.53 and 7.54.

Table 5.4 *Maximum reductions in emissions in the revised Annex VI*

	Global	ECA
NO_x (g/kW·h)	15–20%	80%
SO_x* (g/kW·h)	80%	96%
PM (mass)†(g/kW·h)	73%	83%

* Reduction relative to 2.7% sulphur content in fuel.
† Expected reduction of PM from fuel change.

NO_x

5.86 Reduction of NO_x emissions to Tier III limits (~80% reduction from Tier I) can only be achieved at present by SCR after-treatment or by using LNG as the fuel and lean premixed combustion. These technologies are proven for four-stroke engines; however, experience with large two-stroke engines is limited. A reduction of around 40–50% from Tier I has been demonstrated for four-stroke engines, with a simultaneous improvement in energy efficiency and reduction of emissions of CO_2 compared to current engines [5].

5.87 Using SCR and LNG technology, it is possible to achieve reductions of emissions even beyond Tier III limits at high loads. However, achieving further reductions at low loads and achieving the reduction consistently for extended time periods may be more difficult. Furthermore, the potential for reductions for two-stroke engines is less well documented. Therefore, a primary gateway to reduce emissions of NO_x could be to extend or introduce new ECAs and/or reduce the global NO_x limit. The potential for extending the coverage of ECAs has not been analysed.

SO_x and PM

5.88 The revised MARPOL Annex VI requires significant reductions in emissions of SO_x and of PM, as shown in Table 5.4. While there have been few discussions as to the possibility of reducing emissions of SO_x from individual vessels, there has been debate among experts on the total impact on emissions of CO_2 when these reductions are applied to the world fleet. This is also the case when considering the potential for further reductions. Technically, from the perspective of the ship, further reductions in sulphur are clearly feasible. Indeed, a lower sulphur content in the fuel is purely an advantage for the engine. However, other aspects of the fuel (such as, e.g., lubricity, ignition and combustion properties) are critical to the performance of the engine. Reductions in the sulphur limits of marine fuel may cause marine fuels to be blended in new ways, using different components, which could positively or negatively influence other parameters of the fuel. Therefore, more comprehensive and narrower specifications of marine fuels may be needed in the future.

5.89 A potential for reducing emissions of SO_x and of PM below the levels that are indicated in Table 5.4 by using scrubbing technology has been claimed. Alternative fuels, such as LNG, will also enable emissions of SO_x to be reduced, although such fuels must be expected to be relevant for only part of the fleet. Possible future application of LNG as a fuel for ships is discussed in Chapter 7. The potential for reducing emissions of SO_x through increasing ECA coverage has not been analysed.

CO and NMVOC

5.90 Carbon monoxide and NMVOC are by-products of incomplete combustion. These emissions show a certain trade-off with NO_x, as technologies aimed at reducing NO_x, other than SCR, tend to increase these emissions. Typical levels of these emissions are very low, in the range of 0.1–0.3 g/kW·h, and little effort has been made to reduce them further.

SUMMARY

5.91 Paragraphs 5.91 to 5.94 discuss the potential options for reduction of emissions of greenhouse gases and other relevant substances from the shipping sector, from a technological perspective. In principle, there are four fundamental categories of options for reducing emissions from shipping.

1. Improving energy efficiency, i.e. doing more useful work with the same energy consumption. This applies to both the design and the operation of ships.
2. Using renewable energy sources, such as the wind and the sun.
3. Using fuels with less total fuel-cycle emissions per unit of work done, such as biofuels and natural gas.
4. Using emission-reduction technologies – i.e. achieving reduction of emissions through chemical conversion, capture and storage, and other options.

5.92 The potential for saving energy by combining these options is very significant, as shown in Table 5.2. It has been assessed that, by application of known technology and practices, shipping could be 25–75% more energy-efficient, depending on the ship type and the degree of compromise.

5.93 Renewable energy, in the form of wind and solar energy, can be used on board ships as additional power; however, the total share of energy that can be covered in this way is limited both by the availability and variable intensity of wind and solar energy and the present-day ability to make use of it.

5.94 LNG is a marine fuel that delivers very significant reduction of NO_x, SO_x and PM emissions and also at the same time a reduction in CO_2 equivalents. Where available, LNG is expected to remain a less expensive fuel than distillate fuels. This combination makes it particularly interesting for use within future ECAs. Emission-reduction technologies can be applied to reduce SO_x, NO_x and PM emissions.

REFERENCES

1 Bertram, V. and Schneekluth, B. 1998. *Ship Design for Efficiency and Economy*. Second edition. Butterworth Heinemann. ISBN 0-7506-4133-9 (978-0-7506-4133-3).
2 Wijnholst, N. and Wergeland, T. 2009. *Shipping Innovation*, IOS Press. ISBN 978-1-58603-943-1.
3 Brett, P.O., Boulougouris, E., Horgen, R., Konovessis, D., Oestvik, I., Mermiris, G., Papanikolaou, A. and Vassalos, D. 2006. "A methodology for logistics-based ship design". 9th International Marine Design Conference (IMDC'06), Ann Arbor, Michigan, USA.
4 IMO. 2000. Study of Greenhouse Gas Emissions from ships. MEPC 45/8.
5 Tanaka, Y. 2003. "Economical speed and life cycle value of ship". 4th Japan Towing Tank Conference, The Society of Naval Architects of Japan.
6 Wik, C. and Hallback, B. 2007. "Utilisation of 2-stage turbo charging as an emission reduction means on a Wärtsilä 4-stroke medium-speed diesel engine". CIMAC paper 101; Proceedings of the 25th CIMAC World Congress on Combustion Engines, Wien, Austria, 21–24 May 2007.
7 Buhaug, Ø., Halvorsen, E., Brembo, J.C., Nilsen, J. and Hawkes, R. 2006. Flagship D-B1.1 Influence of external factors on the energy efficiency of shipping, EU IP TIP5-CT-2006-031406.
8 Clauss, G.F., Siekmann, H. and Tampier, B.G. 2007. "Simulation of the operation of wind-assisted cargo ships". 102 Hauptversammlung der Shiffbautechnischen Gesellschaft, 21–23 November 2007, Berlin.
9 Eide, M., Endresen, Ø., Skjong, R., Longva, T. and Alvik, S. 2009. "Cost-effectiveness assessment of CO_2-reducing measures in shipping". Submitted to *Maritime Policy & Management*.
10 Einang, P.M. 2007. "Gas-fuelled ships". CIMAC paper 261; Proceedings of the 25th CIMAC World Congress on Combustion Engines, Wien, Austria, 21–24 May 2007.
11 Bergh, O. 2006. NO_x verifikasjon, B/F "TRESFJORD" MARINTEK report MT28 F06–010.
12 Maeda, K., Takasaki, K., Masuda, K., Tsuda, M. and Yasunari, M. 2004. "Measurement of PM emission from marine diesel engines". CIMAC paper 107; Proceedings of the 24th CIMAC World Congress on Combustion Engines, Kyoto, Japan, 7–11 June 2004.
13 Okada, S., Senda, J., Tsujimoto, K. and Kitagawa, K. 2007. "Physical characteristics of particulate matter emission from medium-speed marine diesel engine". CIMAC paper 59; Proceedings of the 25th CIMAC World Congress on Combustion Engines, Wien, Austria, 21–24 May 2007.
14 Wall, J.C. and Hoekman, S.K. 1984. "Fuel composition effects on heavy-duty diesel particulate emission", SAE Technical paper series 841364.
15 Kurok, C., Pawils, V., Brumm, H. and Götze, H.J. 2007. "Emission of particulate matter from marine diesel engines", presentation at IMO BLG WGAP2, Berlin 2007

16 Ives, R. and Klokk, S. 1993. "Exhaust gas sulphur removal by sea water washing, marine diesel engines". Paper D58; Proceedings of the 20th CIMAC World Congress on Combustion Engines, London, UK, 17–20 May 1993.
17 Bak, F. 2007. "The influence of a SO_x abatement plant on diesel engine emissions". CIMAC paper 99; Proceedings of the 25th CIMAC World Congress on Combustion Engines, Wien, Austria, 21–24 May 2007.
18 CIMAC 2008. "Guide to diesel exhaust emissions control of NO_x, SO_x, particulates, smoke and CO_2 – seagoing ships and large stationary diesel power plants, 2008". CIMAC Recommendation 28. www.cimac.com
19 Schwarz, W. and Rhiemeier, J. 2007. 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.
20 Refrigeration, Air Conditioning and Heat Pumps Technical Options Committee (RTOC), United Nations Environment Programme. 2006 RTOC Assessment report. http://ozone.unep.org/teap/Reports/RTOC/index.shtml
21 Shine, K.P., Fuglestvedt, J.S., Hailemariam, K. and Stuber, N. 2005. "Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases". *Climatic Change*, 68: 281–302.
22 Longva, T., Eide, M.S. and Skjong, R. 2009. "A cost–benefit approach to determining a required CO_2 index for future ship designs". Submitted to *Environmental Science & Policy*.
23 Vallentin, D. 2008. "Driving forces and barriers in the development and implementation of coal-to-liquids (CtL) technologies in Germany". *Energy Policy*, 36(6); 2030–2043.
24 Einang, P.M., "Gas-fuelled ships". CIMAC paper 261; Proceedings of the 25th CIMAC World Congress on Combustion Engine Technology, Vienna, Austria, 21–24 May 2007.
25 Opdal, O.A. and Fjell Hojem, J. "Biofuels in ships: A project report and feasibility study into the use of biofuels in the Norwegian domestic fleet", ZERO report 18 December 2007.
26 Ollus, R. and Juoperi, K. 2007. "Alternative fuels experiences for medium-speed diesel engines". CIMAC paper 234; Proceedings of the 25th CIMAC World Congress on Combustion Engine Technology, Vienna, Austria, 21–24 May 2007.
27 Matsuzaki, S. 2004. "The application of the waste oil as a bio-fuel in a high-speed diesel engine". Proceedings of the 24th CIMAC World Congress on Combustion Engine Technology, Kyoto, Japan, 7–11 June 2004.
28 "Energy and greenhouse gas balance of biofuels for Europe – an update". CONCAWE Ad Hoc Group on Alternative Fuels. Brussels. 2002. http://www.concawe.org/DocShareNoFrame/docs/1/LDHHJOAAEHLEHNCOKCFLBMBEPDBY9DBYW69DW3571KM/CEnet/docs/DLS/2002-00213-01-E.pdf
29 UN-Energy. "Sustainable Biofuels: a framework for decision makers", April 2007, http://esa.un.org/un-energy/pdf/susdev.Biofuels.FAO.pdf
30 IMO. 2008. Ship Efficiency Management Plan. MEPC 58/INF.7.
31 IMO. 2008. "Guidelines for exhaust gas cleaning systems" MEPC.170(57). http://www.imo.org/includes/blastDataOnly.asp/data_id%3D22480/170%2857%29.pdf
32 The Japan Society of Naval Architects and Ocean Engineers Conference Proceedings, Vol. 5W, 2007. "A study of energy-saving navigation planning considering weather forecast data".
33 Takashima, K., Kano, T. and Kobayashi, M. 2008. "Energy saving operation for coastal ships based on precise environmental forecast". *The Journal of Japan Institute of Navigation*, 118; 99–106.

6

Policy options for reductions of GHG and other relevant substances

INTRODUCTION

6.1 Scenarios for future emissions from ships are presented in Chapter 7 of this report. These scenarios show that emissions of GHG from shipping are likely to increase in the future, principally due to an anticipated increased demand for transport. Chapter 3 has identified CO_2 as the most important GHG emission from shipping. Therefore, this chapter emphasizes reduction of emissions of CO_2. Chapter 8, which addresses climate impacts, puts the future emission from shipping in a global context. This is done by comparing scenarios for future emissions of CO_2 from ships with the total global emission of CO_2 that is believed to result in an increase in temperature of 2°C. It is clear from this comparison that reductions in emissions of CO_2 from the shipping sector are needed beyond what is anticipated in the scenarios. Chapter 5 provides examples of technical and operational measures that can be taken to reduce emissions. As some of these measures are costly, policies will be needed to support their implementation. This chapter analyses the policy options that may be applied to achieve reductions of emissions.

6.2 The chapter is structured as follows. Paragraphs 6.4 to 6.33 discuss progress and current work within IMO on this topic. Paragraphs 6.34 to 6.47 provide an analytical overview of policy options, while paragraphs 6.48 to 6.71 describe the design of the policy options to be analysed. Paragraphs 6.72 to 6.130 discuss criteria for analysis of policy options and present a qualitative analysis of these options. Conclusions are provided in paragraph 6.131.

6.3 General background information that is relevant to the discussion is provided in Chapter 2 of this report. This background includes, *inter alia*, introduction to the United Nations Framework Convention on Climate Change (UNFCCC), differences in interpretation of the wording of Article 2.2 of the Kyoto Protocol, and a general overview of regulation and the legislative framework for shipping.

PROGRESS AND CURRENT DISCUSSIONS IN IMO

6.4 In 1997, the MARPOL Conference adopted a resolution on "CO_2 emissions from ships", inviting the IMO to undertake a study on the quantity of GHG emissions from ships and to consider "feasible GHG emission reduction strategies". The MEPC commissioned a study which was completed in 2000 and provided an examination of emissions of greenhouse gases from ships as well as possibilities for the reduction of these emissions through different technical, operational and market-based approaches.

6.5 To further address the issue of GHG emissions from ships, the IMO Assembly adopted (December 2003) resolution A.963(23) on "IMO Policies and practices related to the reduction of greenhouse gas emissions from ships", which, *inter alia*:

1. Urges the MEPC to identify and develop the mechanism or mechanisms needed to achieve the limitation or reduction of GHG emissions from international shipping and, in doing so, to give priority to:
   - the establishment of a GHG emission baseline;
   - the development of a methodology to describe the GHG efficiency of a ship in terms of a GHG emission index for that ship. In developing the methodology for the GHG emission indexing scheme, the MEPC should recognize that CO_2 is the main greenhouse gas emitted by ships;

- the development of Guidelines by which the GHG emission indexing scheme may be applied in practice. The Guidelines are to address issues such as verification; and
- the evaluation of technical, operational and market-based solutions.

6.6 Results from the extensive work within the MEPC in response to this challenge are briefly summarized in the following sections. Paragraphs 6.7 to 6.12 discuss progress towards the establishment of a GHG emission baseline. Paragraphs 6.13 to 6.28 focus on methodologies to describe the GHG efficiency of a ship. Paragraphs 6.29 and 6.30 address the development of guidelines by which the GHG emission indexing scheme may be applied in practice. Paragraph 6.31 briefly describes the evaluation of technical, operational and market-based solutions, although this is also captured by paragraphs 6.48 to 6.71.

The establishment of a GHG emission baseline

6.7 When referring to a baseline for GHG emissions, resolution A.963(23) calls for an overall baseline for total emissions of CO_2 from ships for a given year, with the purpose of illustrating the trends in total emissions. The same resolution also requests that the MEPC consider the methodological aspects related to the reporting of emissions of GHG from ships that are engaged in international trade.

6.8 Establishing a baseline for shipping is a challenging discussion for the MEPC, since the scope of the baseline may or may not be subject to flag, i.e. the still-to-be-resolved question of whether "common but differentiated responsibility" should apply to a GHG regime for international shipping rather than IMO's basic principle of "no more favourable treatment".

6.9 Moreover, there are methodological difficulties in establishing such baselines. This can be appreciated by the discussions in Chapter 3 and Appendix 1 of this report, in which, *inter alia*, it is concluded that statistical data presently available are likely to under-report the consumption of marine fuel. The emissions inventory for this study relies on an activity-based estimate for 2007. As can be seen in Chapter 3, there is a considerable uncertainty in the estimate. In this study, the estimated annual changes in emissions in years prior to 2007 are based on trending with seaborne trade estimates from Fearnleys. While this was found to be the best possible approach for this study, it is inappropriate to rely on data from Fearnleys to calculate future emissions in a framework where direct activity data are instrumental in determining whether or not goals have been achieved.

6.10 Chapter 3 and Appendix 1 of this study exemplify the use of shipping activity input to establish current-year emissions, and demonstrate how to use explicit scenario drivers to articulate future estimates under various interventions and economic signals. This discussion is relevant, since establishing baselines is an important element of some policy options that will be discussed in forthcoming sections.

6.11 The number of days at sea for the various ship types is the parameter in the activity-based inventory that contributes the largest uncertainty. Long Range Identification and Tracking (LRIT) systems may provide data that could provide trends in ship activity that are suitable for an activity-based baseline. The related provisions of the 1974 SOLAS Convention have entered into force on 1 January 2008; the phased-in implementation started on 31 December 2008 and will be completed for passenger ships (including high-speed craft), cargo ships of 500 gross tonnage and above (including high-speed craft), and mobile offshore drilling units (when they are not on location), when engaged on international voyages, by 30 December 2009 (for the SOLAS Contracting Governments which are also Parties to the 1988 SOLAS Protocol, this will be completed by 30 March 2010).

6.12 The cost of LRIT information has to be paid for by those requesting such information, and in essence the total cost of the LRIT system is paid by SOLAS Contracting Governments as flag States. As a result, there are certain caveats in relation to the use and sharing of LRIT information, and thus it will be necessary to discuss certain issues within the Maritime Safety Committee, including amending the current decision so as to allow the use of LRIT information for purposes of protection of the environment. Nevertheless, while some uncertainty is inevitable, it is considered to be technically feasible to generate rigorous baselines, using activity-based data, in the near future.

Methodologies to describe the GHG efficiency of a ship

6.13 Resolution A.963(23) calls for the development of a methodology to describe the GHG efficiency of a ship in terms of a GHG emission index for that ship. Recognizing that CO_2 is the most important greenhouse gas that is emitted from ships, the MEPC has mainly emphasized emissions of CO_2 in their discussions and has explored three principal pathways to indexing emissions:

1. Indexes expressing the GHG efficiency of the design of the ship;
2. Indexes expressing the GHG efficiency of the operation of the ship; and
3. Combinations of the above.

6.14 Emission indexes are designed to benchmark design or performance of ships. This information can potentially be used by shipowners and ship operators for self-improvement. Potentially, emission indexing could be used in voluntary incentive systems or in mandatory schemes, as is discussed in paragraphs 6.48 to 6.71. The remainder of this section describes the two indexes that are currently discussed in IMO, viz. the Energy Efficiency Design Index (paragraphs 615 to 6.23) and the Energy Efficiency Operational Indicator (paragraphs 6.24 to 6.28).

Energy Efficiency Design Index (EEDI)

6.15 The MEPC has considered indexes expressing the GHG efficiency of the design of a ship in great detail. The fundamental principle that has been agreed is that the emission index expresses the ratio between the cost (i.e. emission) and the benefit that is generated, which is expressed as transport work capacity.

6.16 MEPC 58 approved the use of the draft Interim Guidelines on the method of calculation of the Energy Efficiency Design Index for new ships, for calculation and trial purposes with a view to further refinement and improvement, as set out in annex 11 of its report [1]. Since the EEDI has not been finalized at the time of writing (March 2009), it is possible that changes could be made compared to what is presented here. It is likely, however, that such changes will apply only to details of the EEDI, which will have little impact on the overall concept that is discussed here.

6.17 The EEDI expresses the emission of CO_2 from a ship under specified conditions (e.g., engine load, draught, wind, waves, etc.) in relation to a nominal transport work rate. The unit for EEDI is grams of CO_2 per capacity-mile, where "capacity" is an expression of the cargo-carrying capacity relevant to the cargo that the ship is designed to carry. For most ships, capacity will be expressed as deadweight tonnage.

6.18 The EEDI formula takes into consideration special design features and needs, including the use of energy recovery, the use of low-carbon fuels, performance of ships in waves and the need for ice strengthening of certain ships. The handling of certain design features, such as electric propulsion, is still subject to evaluation. The EEDI has a constant value that will only be changed if the design is altered.

6.19 The EEDI provides, for each ship, a figure that expresses its design performance. By collecting data on the EEDI for a number of ships within a category, it will be possible to establish baselines that express typical efficiencies of these ships. Figure 6.1 shows the effect of deadweight of a ship on the CO_2 design index for some categories of ship [2]. The formula that was used to calculate the CO_2 design index is similar to the EEDI, and the EEDI is expected to show the same behaviour.

6.20 Based on this type of analysis, EEDI baselines have been proposed for different ship categories that are functions of ship size [3], where size is expressed, e.g., as deadweight tonnage or gross tonnage. EEDI baselines could be part of different policies using the EEDI. It is clear from this figure, however, that, when the ship size gets very small, the curve showing the EEDI trend becomes steep for these small container ships and dry cargo ships shown. Therefore, small variations in ship size may result in very large variation in the EEDI baseline. This could potentially encourage non-optimal design practices where ship size is selected by the EEDI baseline allowance rather than by operational need, which may not be a desirable outcome. Therefore, a size threshold could be considered for the application of an EEDI baseline of this type.

6.21 Establishing an EEDI baseline, using different datasets, will result in different baselines being calculated. Presently, the EEDI is not finalized and baseline data have been approximated by using data from existing ship databases rather than being obtained through the process of establishing the EEDI for

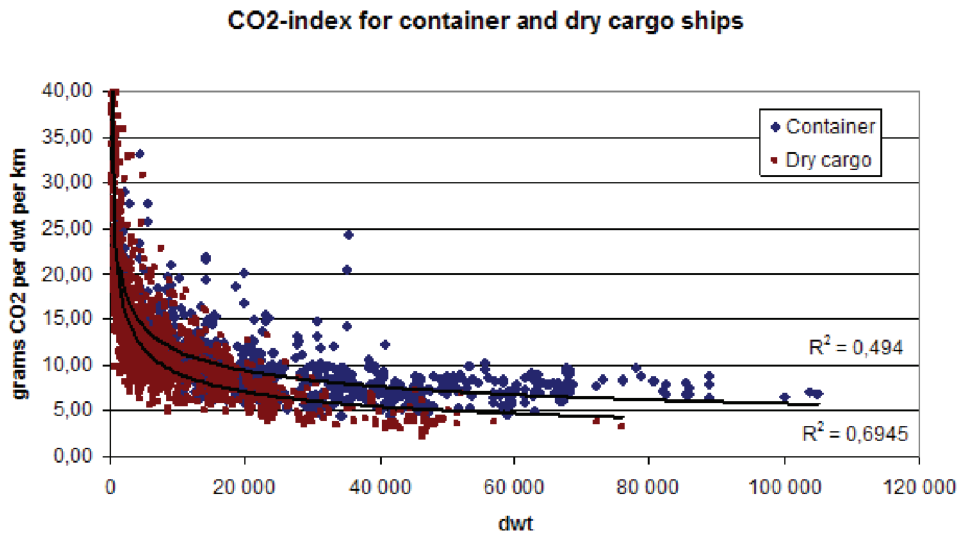


Figure 6.1 *The effect of ship deadweight on CO_2 design index [2]*

individual ships. Also, the introduction of Common Structure Rules (CSR) has increased the steel weight of new ships, which may need to be taken into account. Presently, some work remains within the MEPC to finalize the development of EEDI baselines.

6.22 Some ships are not primarily designed to transport cargo. Examples include tugs, ice-breakers, dredgers, fishing vessels and cruise ships. In these cases, transport work is not suitable to express the benefit they provide [4]. Therefore, there are some ship types where the EEDI, in units per kilometre, may be considered less meaningful or relevant. This, and the possible need for a minimum size threshold, suggests that the units in which EEDI is measured may need modification to address some ship types and sizes, and that the EEDI may not be practically applicable to all ship types. However, large cargo ships can be covered and, as shown in Chapter 3, these ships account for a significant share of emissions.

6.23 Potential policies, using the EEDI as a basic parameter, are discussed in forthcoming sections.

Energy Efficiency Operational Indicator (EEOI)

6.24 The fundamental principle for the EEOI is the same as agreed for the EEDI, i.e. that the emission index expresses the ratio between the cost (i.e. the emission) and the benefit that is generated.

6.25 The EEOI was previously referred to as the (operational) "IMO CO_2 index". The Interim Guidelines for voluntary ship CO_2 emission indexing for use in trials were adopted by MEPC 53 in July 2005 and published as MEPC/Circ.471. The MEPC urged interested parties to facilitate trials and report results. In the work leading to the adoption of MEPC/Circ.471, alternative formulas, approaches and use of the index were discussed, as presented in MEPC 53/WP.3 and MEPC 49/4. At the time of writing (March 2009), IMO is in the process of finalizing an updated version of the EEOI. The final EEOI could, therefore, be somewhat different if compared to the EEOI as discussed here.

6.26 The EEOI expresses actual CO_2-efficiency in terms of emissions of CO_2 per unit of transport work, using the following formula (MEPC/Circ.471):

$$\text{EEOI} = \frac{\sum_i \text{FC}_i \times \text{C}_{\text{carbon}}}{\sum_i \text{m}_{\text{cargo},i} \times \text{D}_i}$$

where:

FC_i denotes fuel consumption on voyage i;
C_{carbon} is the carbon content of the fuel used;
$\text{m}_{\text{cargo},i}$ is the mass of cargo transported on voyage i; and
D_i is the distance of voyage i.

The unit for the EEOI is grams of CO_2 per capacity-mile, where "capacity" is an expression of the actual amount of cargo that the ship is carrying. For most ships, capacity will be expressed as tonnes of cargo moved; however, other units (such as passengers, TEU, cars and more) may also be used. Unlike the EEDI, the EEOI changes with operational conditions. The EEOI may thus be calculated for each leg of a voyage and reported as a rolling average or periodically.

6.27 MEPC/Circ.471 specifies that "the guidelines are applicable for all ships performing transport work".

6.28 From the trials conducted to date, it appears that the value of the EEOI will, amongst others, depend on the average utilization of the cargo-carrying capacity that can be achieved in actual operation. The latter is affected by the cyclical "business climate" for the various trades [5]. Hence the average indicator for a ship category may vary from one year to the next, given changes to demand and competition, and among trade routes. Some transport tasks appear to offer the possibility for high average utilization (e.g., return cargo, or trade triangles), while other trade patterns (e.g., distribution of smaller cargo parcels) may result in inherent low efficiency that is related to the nature and geography of the transport demand, not to the operation or choice of ship [6]. All of these issues may make it hard to establish a baseline for the EEOI.

Applying the GHG emission indexing schemes in practice

6.29 In order to promote best practices for fuel-efficient operation of ships, the MEPC is considering the introduction of a Ship Efficiency Management Plan (SEMP). The shipping industry has put significant effort into the development of the technical details of how this could be done, as presented in MEPC 58/INF.7 [7].

6.30 The SEMP presents a framework for a ship to address energy-efficient operation by monitoring performance and considering possible improvements in a structured fashion. A SEMP could be developed by the ship operator or other relevant party, such as a ship charterer. Its successful implementation would include four phases:

1. Planning;
2. Implementation;
3. Performance monitoring; and
4. Self-improvement.

The EEOI could be utilized for performance monitoring within the SEMP – the SEMP should not be seen in isolation. Provisions already exist in the ISM Code for owners and operators to monitor environmental performance and to establish a programme for continuous improvement. The proposed Ship Efficiency Management Plan may be considered an amplification of the requirements of the ISM Code. It provides a possible mechanism for monitoring ship and fleet efficiency performance over time (based on the EEOI) and some options to be considered when seeking to optimize the performance of the ship [7].

The evaluation of technical, operational and market-based solutions

6.31 One of the tasks that IMO Assembly resolution A.963(23) urges the MEPC to undertake is "the evaluation of technical, operational and market-based solutions". The MEPC has indeed discussed technical, operational and market-based policy instruments. These discussions have not yet resulted in the adoption of a policy. The proposals that were made during these discussions are the basis for paragraphs 6.48 to 6.71, on the design of GHG policies for shipping.

Work plan for IMO GHG work

6.32 As a follow-up to resolution A.963(23), MEPC 55 (October 2006) approved a "Work plan to identify and develop the mechanisms needed to achieve the limitation or reduction of CO_2 emissions from international shipping", inviting Member Governments to participate actively in the work. The work plan culminates at MEPC 59 (July 2009) and contains, *inter alia*, improvement of the method of operational efficiency indexing that is described in paragraphs 6.13 to 6.28 above, establishment of CO_2 emission baseline(s), and consideration of technical, operational and market-based methods for dealing with emissions of GHG from ships in international trade.

6.33 Results from this work will be important to the considerations that will take place within the UNFCCC at the fifteenth session of the conference of the parties (COP-15, December 2009). The overall goal for this conference is to establish an ambitious agreement on global climate.

IDENTIFICATION OF POLICY OPTIONS

6.34 A large number of policies to reduce ships' GHG emissions are conceivable. This section sets out to identify a comprehensive overview of options, abstracting from concrete proposals that have been made to IMO. The next section will discuss the options that are relevant to the current IMO debate in more detail.

6.35 There are various ways to classify policies, we list two.

1. Policies can be classified according to the *basic parameter* that the policy uses. In the case of climate policies, the basic parameter can be absolute emissions, an efficiency indicator, life-cycle carbon emissions arising from a fuel, etc.
2. Policies can be classified according to the *type of policy instrument*. In environmental policies, a classification of market-based instruments, command-and-control[1] instruments and voluntary instruments is often used.

This study identifies policy instruments according to the basic parameter.[2] Paragraphs 6.42 to 6.44 present a matrix where policy instruments are categorized according to both the basic parameter and the type of instrument.

Factors determining maritime emissions of CO_2

6.36 Figure 6.2 presents a stylized overview of the principal factors that influence the magnitude of emissions from seaborne transport. The purpose is to provide a policy-analytical framework to evaluate

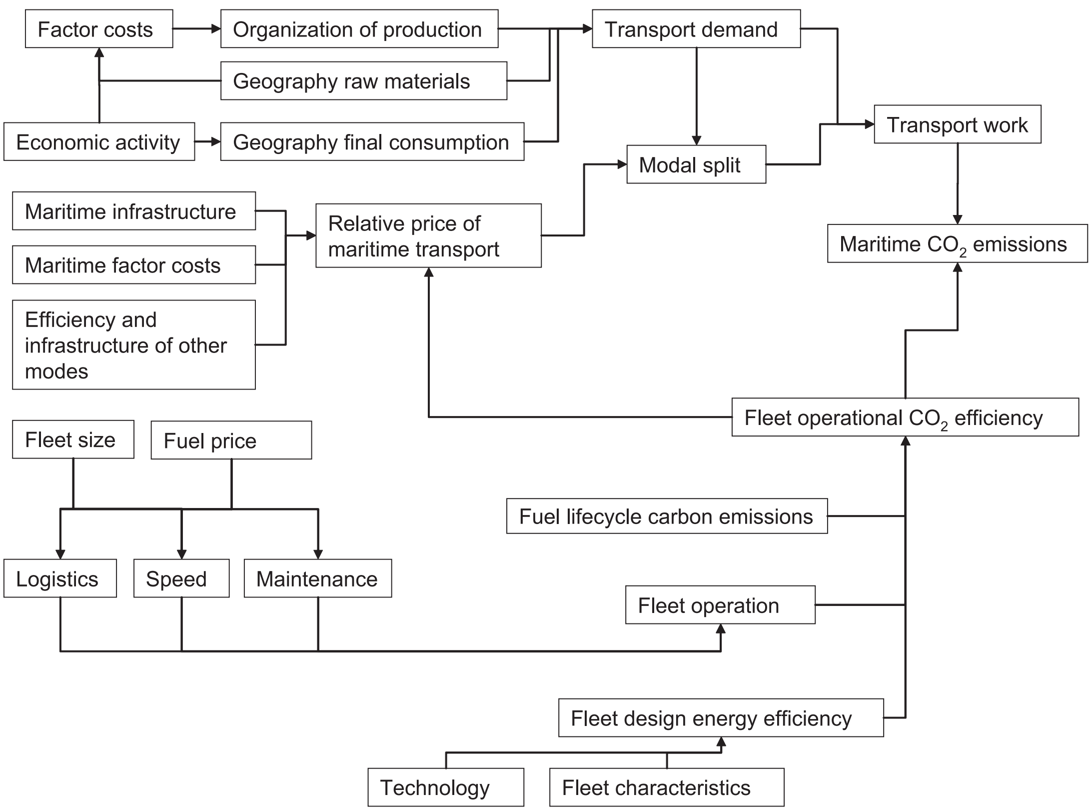


Figure 6.2 *Stylized representation of factors determining maritime emissions*

1 The term "command-and-control" generally comprises all prescriptive regulations, be they prohibitions, technology-based discharge standards, performance standards, etc. (Russell and Powell, 1999 [26]).

2 For a list of policies classified according to the type of policy, see, e.g., Torvanger *et al.* (2007) [29].

options to reduce emissions. Each factor and its direct or indirect relation to maritime emissions will be described in more detail below. Please note that this is a general illustration, not capturing all possible factors and interrelations. This framework is presented here and used in this section because it allows the identification of policy options to reduce maritime emissions of GHG.

6.37 The volume of maritime CO_2 emissions for most ships depends, by definition, on the operational CO_2 efficiency of the fleet (in terms of CO_2 emissions per tonne-mile) and the transport work (in tonne-miles). For non-transport ships, the service-work units could be different (e.g., fishing days, towing/non-towing operating hours, passenger-miles); these are not addressed in this discussion.

6.38 Transport work of the maritime sector depends on two main factors: (overall) demand for transport and the split between modes of transport. Logistic efficiency is also a factor of the actual tonne-miles, although this is not shown in Figure 6.2. In turn, demand for transport is determined by the general economic activity and the geography of raw materials, final consumption and the organization of production. Production tends to be concentrated in areas with low factor costs ("factor costs" being the costs of input factors, such as labour, energy, raw materials, etc.). Both factor costs and geography of final consumption are correlated with economic indicators such as GDP per capita in different parts of the world. Overall GDP level is positively correlated with overall demand for transport. Thus, economic activity (indicated by, e.g., GDP) and geography of raw materials, production and consumption constitute the main driving forces of demand for transport.

6.39 The modal split depends primarily on the availability of alternative modes of transport (not illustrated) and the relative price of maritime transport. The latter depends on the fleet operational CO_2 efficiency, the maritime infrastructure, the factor costs of maritime transport and the prices of competing modes.

6.40 Turning to the operational CO_2 efficiency in the lower half of Figure 6.2, this depends on the fuel life-cycle carbon emissions, on the operation of the fleet and on the fleet design energy efficiency (note that "fleet operational CO_2 efficiency" in Figure 6.2 applies to the fleet, not to individual ships, as the EEOI does. The fleet operational efficiency would be the weighted average of each ship's EEOI). Fuel life-cycle carbon emissions can be changed by a move to fuels such as natural gas and biofuels. The fleet operational aspects that have the largest impact on the CO_2 efficiency are (voyage performance) logistics, maintenance, and speed. All three aspects are influenced by the price of fuel and the size of the fleet relative to demand for transport.

6.41 The fleet design energy efficiency depends on the type of ships in the fleet (e.g., type of engine, size, and shape of a ship) and the use of various energy-saving technologies as outlined in Chapter 5; it is related to the state of the art in shipbuilding at the time when the ships in the fleet were built. (Again, note that "Fleet design energy efficiency" in Figure 6.2 applies to the fleet, not to individual ships, as the EEDI does. The fleet design energy efficiency would be the weighted average of each ship's EEDI.)

Overview of policy options

6.42 In principle, policies can be aimed at each of the factors that determine the maritime emissions of CO_2 as presented in Figure 6.2. In practice, some policies would obstruct free maritime movement or trade, e.g., policies that would directly influence the amount of transport work. The remaining policies can be grouped in four categories, depending on the indicator that is used:

1. Policies directly aimed at reducing maritime emissions of CO_2 without regard to design, operations, or energy source.
2. Policies aimed at improving the operational fuel efficiency of the fleet.
3. Policies aimed at improving the design efficiency of the fleet.
4. Policies aimed at reducing the fuel life-cycle carbon emissions, such as policies that favour the use of natural gas or biofuels.

For each of these basic parameters, a number of policy instruments can be designed. Maritime emissions of CO_2 can be addressed by market-based instruments; operational or design efficiency and the life-cycle carbon emissions can be addressed by market-based instruments or by command-and-control instruments or by voluntary measures. Table 6.1 provides a non-exhaustive overview of policy options.

Table 6.1 *Overview of policies to limit or reduce emissions of GHG from ships*

	Market-based instruments	Command-and-control instruments	Voluntary measures
Maritime GHG emissions	Emissions trading, e.g., METS.* Emissions levy, e.g., ICF.†		
Operational efficiency	EEOI levy. EEOI levy/benefit scheme.	Mandatory EEOI limit. Mandatory EEOI reporting. Mandatory SEMP.	Voluntary agreement to improve EEOI. Voluntary agreement to implement SEMP.
Design efficiency	EEDI levy. EEDI levy/benefit scheme.	Mandatory EEDI limit for new ships.	Voluntary agreement to improve EEDI, meet voluntary standards.
Fuel life-cycle carbon emissions	Differentiated fuel levy.	Fuel life-cycle carbon emissions standard. Biofuel standard.	

* METS – Maritime emissions trading scheme.
† ICF – International Compensation Fund.

6.43 Within IMO discussions, policies are commonly grouped in three categories:

1. Technical policy options, i.e. aimed at improving the design efficiency of the fleet.
2. Operational policy options, i.e. policies aimed at improving the operational efficiency of the fleet.
3. Market-based policy options, i.e. instruments addressing CO_2 emissions directly.

Note that, in the IMO, the phrase "market-based policy options" is generally applied to market-based policy options addressing CO_2 emissions. Market-based options addressing operational or design efficiency are hardly discussed. Throughout this chapter, we will stick to the IMO terminology.

6.44 The above categories are used in the subsequent discussions.

Technical and operational measures in a policy context

6.45 Chapter 5 identifies technical and operational measures that can be taken to reduce the emissions of CO_2 from ships. Depending on the fuel price, some measures are expected to be cost-effective for the operator. It is likely that these measures will be taken on the basis of business-economic considerations by actors in the shipping sector. Other measures are expected not to be cost-effective even when assuming comparatively high fuel prices. These measures will not be taken if business-economic considerations are the sole driver; they have to be incentivized by policies.

6.46 Table 6.2 shows how the principal policy options relate to the emission-reduction options that are presented in Chapter 5. The table shows that technical policy options target design measures in new ships. Operational policy options will, in principle, cover both design options in new ships and operational options in all ships. Market-based instruments cover design measures, operational measures and may imply mechanisms to use emission-reduction options in other sectors.

6.47 A more detailed discussion of the measures that are rewarded by different policies is provided in the discussion on environmental effectiveness and cost-effectiveness of the different policies in paragraphs 6.72 to 6.130.

SELECTION AND DEFINITION OF POLICY OPTIONS FOR FURTHER ANALYSIS

6.48 As shown in paragraphs 6.34 to 6.47, a large number of policies to reduce ships' GHG emissions are conceivable. This section will describe the high-level design of the principal policy options that are discussed within IMO. The purpose of the design is to allow an evaluation of these policy instruments and this evaluation will be based on criteria agreed by MEPC 57 (paragraphs 6.72 to 6.130).

Table 6.2 *Relationship between principal policies and principal emission-reduction options*

	Technical policy options*	Operational policy options†	Market-based instruments ‡
DESIGN (new ships)			
Concept, speed and capability Hull and superstructure Power and propulsion systems	Key aspects can be accounted for in the EEDI or technical standard		
Low-carbon fuels Renewable energy	Capability can be included, but not necessarily used	All design and operational elements may implicitly be covered, as the resulting performance is the basis for the instrument.	All design and operational elements may implicitly be covered, as the resulting CO_2 emissions are the basis for the instruments.
OPERATION (all ships)			
Fleet management, logistics and incentives	No		
Voyage optimization	No		
Energy management	No		
OTHER			
Purchasing reductions from other sectors	No	No	Yes

* Policy aiming to reduce EEDI, or other specific technical standard.
† Policy aiming to reduce EEOI, implementation of Energy Efficiency Management Plan.
‡ Emissions trading system (ETS), International GHG Fund (Compensation Fund).

Technical policy options

6.49 The discussion about technical policy options in IMO focuses on options that are based on what is now known as the Energy Efficiency Design Index (EEDI). As noted, MEPC 58 approved the use of the interim method of calculation for trial purposes, with a view to further refinement and improvement; hence the EEDI is still being developed. This section discusses a mandatory limit on the value of EEDI for new ships, a mandatory reporting of the EEDI for new ships, and a voluntary reporting of the EEDI for new ships.

Policy design features: mandatory EEDI limit value for new ships

6.50 A technical policy option that has been proposed in IMO is a mandatory limit on the value of EEDI for new ships (see, e.g., annex 6 to MEPC 58/4; MEPC 58/4/17; and MEPC 58/4/18). The main design of a mandatory limit on the value of EEDI would be:

- IMO sets a formula for the EEDI;
- IMO agrees on a baseline for the EEDI. The baseline could be established, based on trials with the index. It could be a function of ship type and ship size. The baseline could have the general formula $Baseline\ value = a \square Capacity^{-c}$, where a and c would be ship-type-specific parameters. The baseline could be determined for seven different ship types (MEPC 58/23; MEPC 58/4/8), but extension to other ship types could be possible at a later stage:
  - dry bulk carriers;
  - tankers;
  - gas carriers;
  - containerships;
  - general cargo ships;
  - Ro-Ro cargo ships;
  - passenger ships, including Ro-Ro passenger ships, but excluding high-speed craft;
- IMO sets a target, e.g., a certain percentage below the baseline. Thus, the target would be type- and size-specific. All ships built after a certain date would have to demonstrate that their EEDI is better than the target; and
- IMO decides to tighten the target over time.

Policy design features: mandatory reporting of EEDI for new ships

6.51 This policy would require each ship for which an EEDI can be calculated to report the EEDI upon registration of the vessel. Since the EEDI would be known for every newly built ship, it could be used in schemes like voluntary actions, differentiation of harbour dues, labelling, etc.

6.52 The main design of a mandatory EEDI reporting scheme would be:

- IMO develops guidelines for calculation and verification of the EEDI; and
- IMO requires flag States to register the EEDI of newly built ships.

Policy design features: voluntary reporting of EEDI for new ships

6.53 This policy would allow each newly built ship for which an EEDI can be calculated to report the EEDI. It could then be used in schemes like voluntary actions, differentiation of harbour dues, labelling, etc.

6.54 The main design of a voluntary EEDI reporting scheme would be:

- IMO develops guidelines for calculation of the EEDI; and
- optionally, IMO could consider developing guidelines for verification of EEDI to avoid different criteria in different incentive schemes.

Operational policy options

6.55 Possible use of the EEOI and its predecessor has been discussed by the MEPC on several occasions. Proposals that have been made include:

- mandatory recording/reporting of EEOI;
- mandatory use of the EEOI/SEMP;
- mandatory limit on the value EEOI of combined with a penalty for non-compliance;
- voluntary recording/reporting of EEOI; and
- voluntary use of the EEOI/SEMP.

The design of each of these options will be briefly discussed below.

Policy design features: mandatory recording/reporting of EEOI

6.56 This policy places an obligation on ships to record their EEOI value. The EEOI would then be available for use within the industry and for incentive systems set up by third parties, such as ports. If the values of EEOI were used to trigger benefits in incentive systems, it would be necessary to have a degree of verification of the EEOI values.

6.57 Reporting EEOI data to a central entity has also been proposed as a means to establish baselines for ship efficiency and total emissions. It could then be used in schemes, such as voluntary actions, differentiation of harbour dues, labelling, etc. This is, however, not in itself a policy to reduce emissions; hence this is not discussed here.

Policy design features: mandatory use of the EEOI/SEMP

6.58 A mandatory requirement for a SEMP would imply that ships would be required to document what is done to manage the operational efficiency of each ship. This could be implemented on ships in a fashion similar to the VOC management plan (as mandated by regulation 15 of the revised MARPOL Annex VI). Mandatory use of the EEOI for monitoring performance could be part of this policy. A mandatory use of the EEOI could pave the way for its use in other policies, such as a differentiation of harbour dues, labelling schemes, etc. It is beyond the scope of this report to assess the multitude of possible policy instruments and voluntary actions.

6.59 Verification of the EEOI by an independent third party would only be required if the EEOI were used in incentive schemes.

Policy design features: mandatory EEOI limit value

6.60 In 2008, the GHG working group of the MEPC recommended that the EEOI should not be mandatory, but recommendatory in nature, although it left open the possibility that the EEOI could be made mandatory in the future (MEPC 58/4). A mandatory on the limit on the value of the EEOI could have the following design:

- IMO would determine EEOI baselines after the collection of sufficient data on EEOI of ships. Like the EEDI baseline mentioned above, the EEOI baseline could, in principle, be the best fit of the EEOIs that are reported to IMO. It should be noted that, since the EEOI is not a static figure, this task may be significantly more difficult for the EEOI than for the EEDI (see paragraphs 6.24 to 6.28);
- IMO could set a target for reduction of EEOI, specifying, for example, that the EEOI would have to improve by a certain amount in a certain time period;
- ships would be required to calculate their EEOI regularly, according to appropriate guidelines;
- ships would be required to report their EEOI to their flag State. In order to prevent fraud, a report should be verified by an independent verifier; and
- flag States would take appropriate action if a ship's EEOI did not comply with the limit value. Since the only way in which ships can improve their EEOI is by improving the efficiency of their operation, the penalty for not meeting the limit value could be a financial penalty. This would penalize non-compliant ships while at the same time allowing them to improve their EEOI in the next time period.

Policy design features: voluntary recording/reporting of EEOI

6.61 This policy would allow each ship to calculate and report its EEOI on a voluntary basis. It could then be used in schemes like voluntary actions, differentiation of harbour dues, labelling, etc. Requirements for baselines and for verification of EEOIs could be decided by the schemes where this information would be used.

6.62 The main design of a voluntary EEOI reporting scheme would be:

- IMO develops guidelines including a formula for the EEOI; and
- optionally, IMO could consider developing guidelines for verification of EEOI, to avoid different criteria being used in different incentive schemes.

Policy design features: voluntary use of the SEMP

6.63 A voluntary use of a SEMP would imply that IMO develops a SEMP that is disseminated to shipowners and ship operators, to be used at their discretion.

6.64 The main design of a voluntary use of a SEMP would be:

- IMO develops a Ship Efficiency Management Plan; and
- the SEMP would be disseminated amongst shipowners and operators, to be used at their discretion.

Market-based instruments

6.65 The debate on market-based instruments within the IMO focuses on market-based instruments that address maritime emissions of CO_2, and not, for example, on the market-based instruments that address an efficiency indicator. The two market-based instruments that have received most attention are a maritime emissions trading scheme (METS) and an International Compensation Fund for GHG Emissions from Ships which is based on a global levy on marine bunkers; the Fund is referred to in this document as "ICF".

6.66 The market-based instruments under discussion in IMO share a number of characteristics:

1. both schemes could, in principle, be applied globally and to all ships;
2. both schemes would raise the costs of using fuel, thus creating an additional incentive to improve the fuel efficiency of each vessel;

3. both schemes would need a central organization to manage the scheme;
4. as proposed, both schemes would raise funds, which could be used for a number of purposes. It has to be noted, however, that, in general, raising revenue is not a central element to an emissions trading scheme while, of course. it is a central element to a levy;
5. both schemes would need to set up an organization that manages the fund; and
6. both schemes would require careful legal analysis. The legal aspect has generally not been considered in this report; however the basic framework is outlined in Chapter 2.

6.67 The main differences between the two instruments would be:

1. the METS would limit the net contribution of the maritime sector to global emissions of CO_2. If emissions in the maritime sector would increase, this could only be realized when emissions in other sectors are simultaneously reduced; the ICF would not have this design feature;
2. the METS would contribute to a reduction of global emissions of GHG by increasing the incentive to improve the efficiency and by requiring responsible entities that emit more than the cap to buy allowances from other sectors;
3. the ICF would contribute to a reduction of global GHG emissions by increasing the incentive to improve the efficiency and by buying offsets from other sectors from the Fund; and
4. the ICF would have constant levies for four-year periods; the price of emission allowances in the METS is set by the market and may be volatile.

Design features of an international compensation fund (ICF)

6.68 The design of an international compensation fund, based on a global levy on marine bunkers, is presented in several submissions to IMO (MEPC 56/4/9; MEPC 57/4/4; MEPC 57/INF.13; GHG-WG1/5/1; MEPC 58/4/22). Note that the name of this option that is used in the MEPC does not highlight the main difference between this market-based option and the METS. After all, both proposed options have the feature of raising revenue for an international compensation fund (see paragraphs 6.70 and 6.71). Their difference in this respect lies in the way in which revenues are raised: the ICF raises revenues by a fuel levy, whereas the METS raises revenue by auctioning allowances.

6.69 The design that is presented here is based on these submissions. The main design features are:

1. All ships in international trade would become subject to a levy on bunker fuel, established at a given cost level per tonne of fuel bunkered. Such a levy should apply to all marine fuels, taking due account of different emission factors;
2. The levy could either be paid by the ships, by the suppliers of bunker fuel or by oil refiners. All three are discussed in GHG-WG 1/5/1. We add the following:
   - in the first case, it could be enforced on ships flying a flag of a non-party by port State control of parties when a ship is in the port of a party;
   - in the latter case, suppliers of bunker fuel in non-parties would not be required to pay the levy. In order to avoid evasion, a provision would have to be made that ships would have to pay the levy instead, which then could be enforced through flag and port State control;
   - since requiring suppliers of bunker fuel to pay the levy would need a provision that, in some cases, ships would have to pay, the scheme could be simpler to understand and easier to implement if ships would be liable to pay the levy;
3. A central organization would assign a unique account to each ship, keeping track of all of its purchases of bunkers and payments of levies. Such a system would rely on the ship itself (i.e. its owner/company) paying the levy into the ship's account immediately following bunkering. The ship would have a receipt for such a payment to show in a port State control;
4. The levy is channelled to an International Maritime Greenhouse Gas Emission Fund, managed by parties/organizations yet to be determined;
5. Contracting parties will set clear guidelines for the specific use of the funds. In general, the Fund could distribute the money for the following purposes:

- acquisition of emission allowances generated in other industrial sectors, such as, for example, CDM credits or other project-based credits;
- funding of non-vessel-specific reduction of GHG emissions and/or adaptation projects (CDM and/or JI);
- funding R&D in shipping; and
- funding of an IMO Technical Cooperation programme to improve the efficiency of the world fleet.

Design features of a maritime emissions trading scheme (METS)

6.70 The design of a METS is presented in several submissions to IMO (GHG-WG 1/5/3; GHG-WG 1/5/5; GHG-WG 1/5/6; GHG-WG 1/5/7; MEPC 58/4/19; and MEPC 58/4/25). It should be noted that many of these submissions have the element of an international fund, like the International Compensation Fund described above. The difference between the two is the way in which the fund is financed. In the case of a METS, it is done by auctioning the emission allowances, whereas in the case of an ICF it is by imposing a levy on bunker fuels.

6.71 The design that is presented here is based on the submissions that are cited above. The main design features are:

1. The scope of the scheme would be global and cover emissions of CO_2 from all ships above a certain size threshold. However, the instrument would allow modifications to its scope in order to avoid undesirable negative impacts.
2. A cap on global maritime emissions would be set, based on historical emissions and a target for their reduction. In line with the findings of the IPCC that global emissions need to be limited in absolute terms in order to reduce, delay or avoid impacts on climate change (IPCC 2007 [20]), the cap could be an absolute emissions target. As the cap would apply to global maritime transport, it seems logical that it should be established by an appropriate international organization.
3. Apart from trading between ships within the scheme, the scheme would be open for trade with other emissions trading schemes. The advantages would be that this would enable the shipping sector to buy allowances from other sectors, which may allow the shipping sector to reduce emissions at a lower price compared to the abatement costs in the shipping sector. By opening the METS to allow the use of allowances from other sectors, the price volatility would be significantly reduced, because more sectors, with different business cycles, would be included. Moreover, by allowing the use of project credits from developing countries (such as CDM credits), the METS could finance mitigation in developing countries.
4. The responsible entity, i.e. the entity that will be responsible for monitoring and reporting emissions and surrendering allowances, will be the ship. This ensures that the ship can be held liable if it is not compliant. However, since the ship cannot surrender allowances itself, in practice it is the ship operator, the charterer or the consignee who may surrender allowances for the ship's emissions. From the regulator's point of view, it is not important who surrenders the allowances, as long as they are surrendered, so it is left to the parties who are involved in shipping to contractually arrange the responsibility for surrendering the allowance. Ships will have to monitor their fuel consumption in a verifiable way.
5. The responsible entity will report emissions annually to the flag State and surrender the corresponding amount of allowances. Ships registered in non-parties should be given the possibility to surrender allowances to another party or entity. Port States could inspect whether ships have surrendered allowances.
6. There are several options to allocate allowances initially to the individual ships:
   - selling or auctioning allowances;
   - free allocation, based on former emissions or activity (tonne-miles) of individual ships;
   - free allocation, on the basis of a benchmark;
   - a combination of the above;

7. Each of the above options has a different impact on the sector, a different reward for early action and a different efficiency. In choosing a way, a balance can be struck between economic efficiency, administrative burden and impact on the sector.
8. If it is decided that allowances will be auctioned, the proceeds of the auction may be used to finance a fund that can be used to support adaptation in developing countries and/or R&D in the shipping sector.
9. An administrative organization would have to be set up to manage the fund in case of full or partial auctioning of allowances.

ASSESSMENT OF POLICY OPTIONS

Assessment criteria

6.72 At MEPC 57, it was agreed that a coherent and comprehensive future IMO regulatory framework on GHG Emissions from ships should be (MEPC 57/21):

- effective in contributing to the reduction of total global emissions of greenhouse gases;
- binding and equally applicable to all flag States, in order to avoid evasion;
- cost-effective;
- able to limit – or, at least, effectively minimize – competitive distortion;
- based on sustainable environmental development without penalizing global trade and growth;
- based on a goal-based approach and not prescribe specific methods;
- supportive of promoting and facilitating technical innovation and R&D in the entire shipping sector;
- accommodating to leading technologies in the field of energy efficiency; and
- practical, transparent, fraud-free and easy to administer.

However, the second principle was not accepted by all delegations.

6.73 In the following, we condense the nine criteria into four in order to improve the readability of the analysis. We do so on the following arguments:

1. MEPC 57's second criterion – equal applicability to all flag States – can be applied to all policies discussed here.
2. MEPC 57's fourth criterion – minimization of competitive distortion – is assessed when evaluating environmental effectiveness and cost-effectiveness. After all, markets would be distorted if the policy affects certain parts of the market differently from other parts. This could mean that the environmental goal would affect only parts of the shipping market, so that the reduction or limitation of emissions would be less. Alternatively, it could mean that the burden of reaching the goal would weigh more heavily on some parts of the market than on others. In that case, the cost-effective measures in the parts of the market that are not affected will not be taken, so that the average cost-effectiveness deteriorates. Thus, competitive distortion reduces both the environmental effectiveness and the cost-effectiveness.
3. The environmental effectiveness and cost-effectiveness together indicate the degree to which MEPC 57's fifth criterion is met – sustainable environmental development without penalizing global trade and growth.
4. MEPC 57's sixth criterion is met by all policies under consideration, as neither of them prescribes specific methods.

6.74 Please note that we do not discard any of the criteria set by MEPC 57 but rather condense them in order to reduce repetition of arguments. The criteria that will be used in this report are:

- the environmental effectiveness, i.e. the extent to which the policy is "effective in contributing to the reduction of total global greenhouse gas emissions" (first criterion of MEPC 57);
- the cost-effectiveness (third criterion of MEPC 57);

- the incentive to technological change (seventh and eighth criteria of MEPC 57 as technical change is understood to be the development and adoption of new technologies – R&D and innovation – and the accommodation of current technologies); and
- practical feasibility of implementation (ninth criterion of MEPC 57).

Assessment of environmental effectiveness

6.75 The environmental effectiveness of policies depends on the supply of measures that reduce emissions and the demand for reduction of emissions. While the demand is set by the target, cap or level of a levy (which is a political decision), this section focuses on the four factors that determine the supply:

1. the amount of emissions under the scope of the policy – the larger the amount, the more effective the policy can be;
2. impacts on emissions in non-shipping sectors;
3. the measures that actors can take in order to be rewarded by the policy – the larger the potential emission reductions of the measures, the more effective the policy can be; and
4. applicability of the policy instrument – policies that can be evaded or that suffer from a rebound effect or free riders are less effective.

Each of these factors will be discussed below. They will only be applied to policy instruments that go beyond a reporting requirement, as the effectiveness of these instruments depends on the use that is being made of the reported data in other policies, such as, for example, a scheme of differentiated harbour dues or labelling. It is beyond the scope of this report to assess the effectiveness of these schemes.

Amount of emissions under the scope of the policy

6.76 The amount of emissions under the scope of a policy depends on possible limitations with respect to which types or groups of ships are affected by the policy. Such limitations can be technically motivated. For instance, the EEOI and EEDI and/or respective baselines may not be defined for all ship types. Limitations to the scope of a policy may also be administratively motivated; for instance, a size threshold to limit the number of ships that are covered by the policy. It is also possible to impose geographical limitations to the application of a policy. Each of these will be discussed below.

6.77 Technical policy options that have been considered by the MEPC are based on the EEDI. Currently, the EEDI is applicable to dry bulk carriers, tankers, gas carriers, container ships, general cargo ships, ro-ro cargo ships; and passenger ships, including ro-ro passenger ships, but excluding high-speed craft (MEPC 58/4/8). The number of ship types may be expanded in the future, but this would require changing the formula or drafting additional formulae for other ship types. Taken together, these types are estimated to have emitted about 81% of the maritime emissions of CO_2 in 2007 (see Chapter 3). So the environmental effectiveness of policies that are based on the EEDI in its current form would be about 19% less than the effectiveness of policies that apply to the entire fleet.

6.78 The EEOI, in its current form, is applicable to all ships carrying cargo (MEPC/Circ.471). In 2007, emissions from these ship types amounted to about 84% of total emissions from ships (see Chapter 3). Consequently, the environmental effectiveness of policies that are based on the EEOI in its current form would be about 16% less than the effectiveness of policies that apply to the entire fleet.

6.79 The SEMP and the market-based instruments that are based on emissions of CO_2 can, in principle, cover all ship types. Hence, their environmental effectiveness is not limited in this respect. It should be noted that MEPC's debate on the possible scope of market-based instruments has not been concluded.

6.80 A size threshold will limit the amount of emissions that are under the scope of the policy. The data on emissions per size category in Chapter 3 suggest that, for most ship types, the relation between size and emissions is an inverted U. In other words, while small ships emit less per ship, there is a large number of small ships, so that the total emissions in a size category have a maximum value for mid-sized ships. So, excluding the categories of smallest ship size has little impact on total emissions. But the impact increases quickly with the size threshold.

6.81 The geographical scope of all of the policies that are discussed here could be global, in which case it would not limit the environmental effectiveness. This would be in line with the existing IMO treaty instruments and with resolution A.963(23), which was drafted by MEPC 49. In the drafting, the MEPC "agreed that the draft Assembly resolution on IMO Policies and Practices related to reduction of greenhouse gas emissions from ships should be based on a common policy applicable to all ships, rather than based on the provisions of Kyoto Protocol which states that the reduction of greenhouse gas emissions is under the responsibility of the Annex I countries of the Protocol" (MEPC 49/22, paragraph 4.9).

6.82 However, it is also conceivable to apply a regional differentiation to the policy, in line with the principle of "common but differentiated responsibilities" in the UNFCCC. One of these options would be differentiation according to the flag of a ship. In that case, because of the ease with which the flag can be changed, the environmental effectiveness of any policy would be severely reduced (Faber *et al.*, 2007 [15]). After all, any policy will lead to increases in cost, and, if only ships that are registered in certain countries face these increases while the cost of registering in other countries is low, it would be rational to register in countries that are not covered by the policy. A similar argument may be made for the country of ownership of a vessel, as it is relatively easy to set up a legal entity which owns a ship in a country that is not covered by the policy.

6.83 In contrast, differentiation according to the route of a vessel or a cargo route would reduce the amount of emissions under the scope, but, provided that shipping routes are not affected significantly, a significant share of global emissions would remain under the scope of the policy. Thus the environmental effectiveness would be reduced less severely.

6.84 In summary, an analysis of emissions that are within the scope of different policy instruments leads to the following conclusions:

1. the amount of emissions covered by market-based instruments that are based on emissions of CO_2 are not restricted by the ship types within the scope of the instruments;
2. the amount of emissions covered by EEOI, as presently defined, is roughly estimated to be about 84% of the global total;
3. the amount of emissions covered by EEDI, as presently defined, is roughly estimated to be about 81% of the global total;
4. the environmental effectiveness of policy instruments that are differentiated according to the route of the vessel or the route of the cargo is less than the effectiveness of uniform policies, but this report could not assess how much smaller the scope would be; and
5. the environmental effectiveness of policy instruments where application is differentiated according to the flag or the owner of a vessel is likely to be very low.

Impacts on emissions in non-shipping sectors

6.85 The environmental effectiveness of a policy depends not only on the reduction of emissions in the shipping sector but also on possible effects in other sectors. Depending on the policy instruments, these effects can either be an increase in the emissions by other sectors or a decrease. The first is most likely to be caused by a modal shift away from maritime transport. The second is most likely to be caused by offsetting emissions. Both are discussed below.

6.86 Shifting to alternative modes of transport is likely to be an issue primarily in short sea shipping. This assumption is supported by evidence on price elasticities and cross-price elasticities. While the price elasticity of demand for shipping is generally low (see above), it is much higher for short sea shipping and inland shipping. Beuthe *et al.* (2001) [13] estimate the price elasticities for inland shipping in Belgium to be between –1.3 for longer distances and –2.6 for shorter distances. Oum *et al.* (1990) [25] found that the demand for inland shipping of coal is inelastic, while the demand for inland shipping of wheat and oil is much more elastic. While these studies focused on inland shipping, the same may apply to short sea shipping. In Australia, the price elasticities of domestic shipping are estimated to be –0.8 on average, much higher than the price elasticity of international shipping (Bureau of Transport and Communications Economics, 1990 [12]). While there is scant evidence on cross-price elasticities, it seems reasonable to assume that the much higher price elasticities in inland and short sea shipping are due to competition with other modes of transport, such as rail and road transport.

6.87 The analysis of the available evidence of own- and cross-price elasticities in short sea shipping indicates that, if the price of sea transport increases relative to road transport and rail, there would be a shift away from the maritime mode of transport. Conversely, if road transport and rail become more expensive, e.g., because of fuel excise duties or because of the inclusion of power generation in an emissions trading scheme, there would be a modal shift towards short sea shipping. If the costs of shipping and land-based transport rise simultaneously and to the same extent, no modal shift will occur.

6.88 Hence, policies that increase the cost of shipping may induce a modal shift in short sea shipping only if the costs of other transport modes are not increased simultaneously. As voluntary policies are unlikely to increase the cost of shipping, the risk of modal shift is highest for the mandatory EEDI and EEOI limits, for the METS and for the ICF.

6.89 Of the policy instruments that have been considered in this chapter, two have an offsetting mechanism in their design:

1. the ICF can use some of the funds that are generated by the fuel levy to buy emission allowances from other sectors or generated by other sectors; and
2. the METS will link to other emissions trading schemes, thus bringing emissions from different sectors and regions under one cap; in addition, a fund could be created by auctioning allowances and a share of this may be used to buy emission allowances from other sectors or generated by other sectors.

So, while the offsetting mechanism of the ICF depends on the share of funds that are made available to buy emission allowances from other sectors, the METS has, as a central design element, the feature that any emissions of the shipping sector above the cap will have to be offset by reductions of emissions in other trading schemes to which the METS is linked. In other words, in the ICF the offsetting is determined by the fund, while in the METS it is determined by the cap and the emissions in the shipping sector.

6.90 In summary, an analysis of the impacts on emissions in non-shipping sectors by modal shift and offsetting leads to the following conclusions:

- modal shift is most likely to occur in short sea shipping and depends on the increase of cost price of shipping relative to other transport modes, such as rail and road transport. All policies that increase the cost of short sea shipping may give rise to modal shift; and
- both market-based instruments allow for offsetting emissions in other sectors. The METS design ensures that the amount of offsetting corresponds to the environmental goal, while the amount of offsetting in the ICF is not explicitly linked to an environmental goal.

Measures awarded under the policy

6.91 Not all measures that reduce emissions can be used for compliance. The range of available measures depends on the type of policy. As noted in Table 6.1, technical policy options that are based on the EEDI reward improvements on newly built ships. Operational options that are based on the EEOI also reward operational options on existing ships. Market-based instruments reward all options, including options in other sectors.

6.92 The quantification of these differences can only be tentative, as the marginal abatement cost curve that is presented in Chapter 5 does not cover all technical and operational measures to reduce emissions (notable measures that have not been included in the marginal abatement cost curve are recovery of waste heat, diesel-electric propulsion, azipod systems, and solar power). Table 6.1 provides a more comprehensive overview. Nevertheless, Figure 6.3 attempts to illustrate the difference between EEDI-based and EEOI-based options.

6.93 Figure 6.3 shows the cost-effectiveness and abatement potential of measures assessed in the marginal abatement cost curve in this report (see Appendix 4). As stated in Chapter 5, a MACC plots the maximum achievable reductions against estimated cost-effectiveness.

6.94 In Figure 6.3, the green line reflects measures that could be used for compliance with EEDI-based policies, assuming that the EEDI would also reward retrofit measures to the hull shape, to the propeller

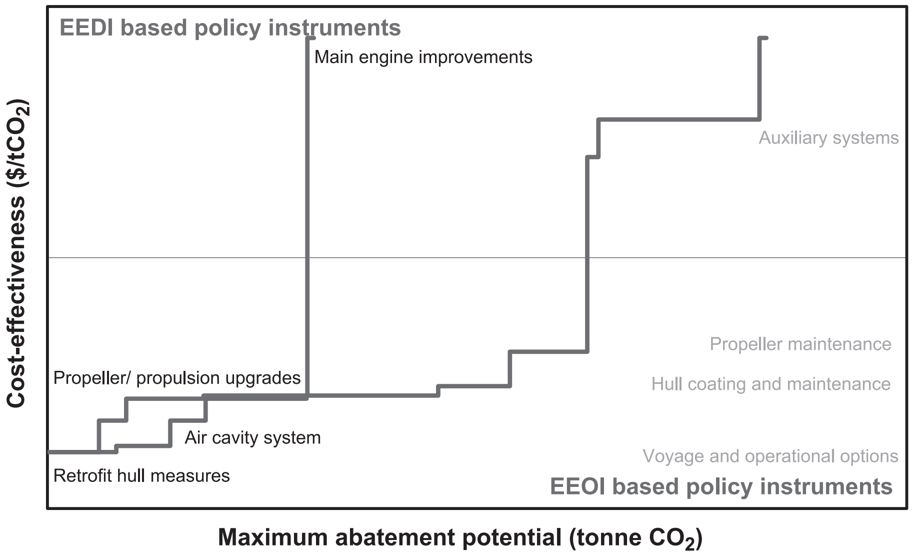


Figure 6.3 *Marginal abatement cost curves for 2020, with fuel at US$500 per tonne*

and propulsion system and to the main engine. Note that, since it has been assumed that retrofits would also be rewarded, the EEDI that is shown by this curve would also apply to existing ships and would not change much when more newly built ships enter the fleet. The red line reflects the measures that could be used for compliance with EEOI-based policies. As can be seen, these include the previous set but add operational and maintenance options.

6.95 In both cases, the maximum abatement potential of each measure (its width on the *x*-axis) assumes that the measures are implemented in each ship type to which they can be applied and that would be included in the policy instrument.

6.96 The graph shows that the cost-effective abatement potential of EEDI-based policy instruments is about half of the cost-effective abatement potential of EEOI-based policy instruments. The total potential of measures assessed in an EEOI-based policy instrument is indicated to be over 2.5-times the total potential of measures assessed in an EEDI-based policy instrument. Since the EEDI would only apply to new ships, the difference is much larger in the short term. The differences between the EEDI and the EEOI marginal abatement cost curves originate in the fact that the EEDI only rewards technical measures whereas the EEOI also rewards operational measures to reduce emissions (see Table 6.2).

6.97 Market-based instruments based on CO_2 emissions reward all of the measures to reduce emissions that are rewarded in an EEOI-based policy. Hence, their abatement potential would be at least as large. Moreover, as noted in paragraphs 6.85 to 6.90, market-based instruments allow for measures to be taken in other sectors.

6.98 One measure to reduce emissions that is not included in the marginal abatement cost curve is a reduction in demand. All policies that require ships to take measures that are not cost-effective increase the cost of shipping, and may therefore reduce demand. The impact of the price on demand is given by the price elasticity of demand. In shipping, this elasticity appears to be low, with the exception of short sea shipping (see paragraphs 6.85 to 6.90) – although the number of estimates is limited. In a review study, Oum *et al.* (1990) [25] find values between –0.06 and –0.25, implying that a 10% increase in the cost of shipping would reduce demand by 0.6% to 2.5%. Meyrick and Associates *et al.* (2007) [23] report similar figures. Hence, the effect of demand is considered to be small.

6.99 In summary, an analysis of the measures that can be used for compliance with different policy instruments leads to the following conclusions:

- METS, ICF and policies based on the EEOI are not restricted by the measures that can be used for compliance; and
- the EEDI is restricted by the measures that can be used for compliance, and the short-term potential is limited due to its application to new ships only.

Applicability of the policy instrument

6.100 In addition to the scope of the emissions under a policy instrument and the measures that can be used for compliance, the environmental effectiveness is affected by the possible rebound effects of a policy, and by the possibilities for evasion and free riders. These will be discussed in this section.

6.101 In general, policies aiming at improving the efficiency, whether it is operational or design efficiency, may suffer from a rebound effect [8]. The "rebound effect" is the effect that an improvement in the efficiency often translates into a much smaller reduction in emissions. The reason is that, as the efficiency improves, the marginal costs often decrease (shipping becomes cheaper), which in turn increases demand. The rebound effect is larger if the demand is price-sensitive, i.e. if the price elasticity of demand is high. In shipping, the scarce evidence that is available suggests that the price elasticity is low. Reported price elasticity is in the range from –0.06 to –0.25 [9]. The only exception seems to be transport of general cargo in short sea shipping, as noted in paragraphs 6.85 to 6.90. For all other types of maritime transport, the rebound effect is likely to be small.

6.102 In general, policies can be evaded if their scope is limited. Please note that "evasion" is not used here in the sense of something illegal – it is distinct from fraud in the sense that "evasion" makes use of the legal possibilities not to comply with it that a policy instrument offers. In the context of climate policies for shipping, we see three possibilities for evasion:

1. If policies apply to certain ship types and not to others, and if the function of these ship types overlaps, operators could evade the policy by using the ship types that are not included in the scope of the policy:
   - Technical policy instruments based on the EEDI and operational policy instruments based on the EEOI apply to a limited number of ship types. However, since the ship types that are included in the EEDI and EEOI are essentially all cargo ships, and since there is little overlap in function between cargo ships and non-cargo ships, the scope for evasion seems to be small.
2. If policies have a certain size threshold, operators could evade the policy by using a ship just below the size threshold instead of a ship that is just over the threshold:
   - The proposals for market-based instruments that are based on emissions of CO_2 are intended to have a size threshold of 400 GT. Probably this would also apply to the other policy instruments discussed here. A quick survey of the ships just below and just above 400 GT shows that a large majority of these ships are service vessels (dredgers, tugs, research vessels), fishing vessels, passenger vessels and ferries, including Ro-Ro ferries. The number of cargo ships is low, and most of these ships are general cargo vessels. So the possibilities for evasion are mainly to be found in the "other" ship types that are not included in the technical and/or operational policy instruments anyway. Hence, this type of evasion is likely to be relevant mainly for market-based instruments based on CO_2 emissions. We are not in a position to quantify the scope for this type of evasion.
3. If policies are differentiated on the route of a vessel or of the cargo, they may be evaded by changing the route of the vessel:
   - In market-based instruments that are based on CO_2 emissions, depending on the way in which "route" is defined in the policy instrument, ships may make an additional port call in a port outside the geographical scope of the policy or may offload their cargo there. It is likely that ships will evade the system if it is profitable to do so, i.e. if the additional costs associated with the evasion are less than the benefits of not having to pay a levy or surrender allowances. We have insufficient evidence to quantitatively assess the costs and benefits, but can only state qualitatively that this type of evasion is more likely if the level of the levy or the price of the emission allowances is high.
   - In command-and-control policy instruments based on either the EEDI or the EEOI, operators may shift their non-compliant ships to regions that are not covered in the geographical scope of the instrument. Again, we have insufficient evidence to quantitatively assess the likelihood of this type of evasion.

6.103 The environmental effectiveness of climate policy for shipping may be affected by the scope for modal shift. If, for example, climate policy results in higher prices for shipping, cargo may be shifted from maritime transport to other modes of transport. While this would reduce the emissions in the maritime sector, it would increase total emissions because other modes have lower transport efficiency (see Chapter 9).

6.104 Free riders are most likely to occur in voluntary agreements, which, by nature, are not enforced by other means than social pressure. Free riding is likely to become more frequent as the costs of compliance of a policy increase. Hence, the environmental effectiveness of a voluntary policy would be limited to cost-effective measures, as costly measures are likely to suffer from free riders. In a more general sense, the environmental effectiveness of voluntary agreements is low in most cases, as has also been found by the OECD [9].

Summary and conclusion on environmental effectiveness

6.105 This section has assessed the impact of four factors on the environmental effectiveness of policy instruments:

1. the amount of emissions under the scope of the policy;
2. impacts on emissions in non-shipping sectors;
3. the measures that actors can take in order to be rewarded by the policy; and
4. the type of policy.

Table 6.3 presents a summary of the conclusions on each of these factors for the policy instruments that are discussed in the section.

6.106 In general, it is concluded that:

1. Since market-based instruments can be applied to all ship types and sizes and allow for all types of measures to reduce emissions, including measures in other sectors, they have a large potential environmental effect.
2. The environmental effect of the METS is determined by the cap, whereas the environmental effect of the ICF depends on the amount of funds made available to buy offsets from other sectors.
3. Since operational policy instruments based on the EEOI are currently applicable to emissions from ships engaged in transport work and allow for all types of measures to reduce emissions in the shipping sector, they have a somewhat smaller environmental effectiveness than either the METS or the ICF. If the EEOI can be developed to include all ship types, the environmental effectiveness of a mandatory limit value would become similar to the environmental effectiveness of market-based instruments.
4. Since technical policy instruments that are based on the EEDI are currently applicable to emissions from new cargo ships and allow for technical measures to reduce emissions, their environmental effectiveness is lower than the effectiveness of operational policy instruments. If the EEDI can be developed to include all ship types, the environmental effectiveness would increase. Also, it would increase over time, as the share of new ships in the fleet increases. However, because technical policy instruments only allow for technical measures to reduce emissions, the environmental effectiveness will still be lower than the effectiveness of operational policy instruments.
5. Regardless of the choice of policy instrument, regionally differentiated policies have a lower environmental effectiveness as they have fewer emissions in their scope and may give rise to evasion.
6. Regardless of the choice of policy instrument, the environmental effectiveness of voluntary agreements is likely to be low because of the possibility of free riding.

Cost-effectiveness

6.107 The cost-effectiveness of a policy option depends primarily on:

- the cost-effectiveness of the emission-reduction measures that are rewarded; and
- the administrative costs related to the implementation and the operation of the policy scheme.

Table 6.3 *Summary assessment of environmental effectiveness of policies*

Evaluation criteria	Technical policy options	Operational policy options			Market-based instruments	
	Mandatory EEDI limit for new ships	**Mandatory use of SEMP**	**Voluntary use of SEMP**	**Mandatory EEOI limit**	**METS**	**International Compensation Fund**
Amount of emissions under the scope of the policy	Currently not so large, as it is only applicable to new ships. May increase in future to ~81% of all emissions unless the formula is changed to include more ship types	Large, since all ships can, in principle, be required to develop a SEMP	Depending on the take-up of such a voluntary measure	Currently limited to ~84% of all emissions. May be expanded in the future if the formula is changed to include more ship types	Large, since all ships can, in principle, be covered by the METS	Large, since all ships can, in principle, be covered by the ICF
The impacts on emissions in non-shipping sectors	Possible modal shift in short sea shipping	Modal shift is unlikely as SEMP would not significantly increase the cost of shipping	Modal shift is unlikely as SEMP would not significantly increase the cost of shipping	Possible modal shift in short sea shipping	Possible modal shift in short sea shipping; reduction of emissions in other sectors to ensure that the cap for shipping is met	Possible modal shift in short sea shipping; reduction of emissions in other sectors is possible
Measures allowed to reduce emissions	Design measures for newly built ships, accounting for ~50% of all conceivable measures in the shipping sector	As a management plan, a SEMP does not require reducing emissions. It will identify cost-effective ways to reduce emissions	As a management plan, a SEMP does not require reducing emissions. It will identify cost-effective ways to reduce emissions	Operational and design measures in the shipping sector, i.e. all conceivable measures in the shipping sector	Operational and design measures in the shipping sector and measures in other sectors	Operational and design measures in the shipping sector and measures in other sectors
Applicability of the policy instrument	Evasion is possible if the geographical scope is limited	Evasion is possible if the geographical scope is limited	May suffer from free riders	Evasion is possible if the geographical scope is limited	Evasion is possible if the geographical scope is limited	Evasion is possible if the geographical scope is limited

Each factor will be analysed below for policy instruments that go beyond a reporting requirement. The reason is that the cost-effectiveness of reporting instruments depends on the use that is being made of the reported data in other policies, such as, for example, a scheme of differentiated harbour dues or labelling. It is beyond the scope of this study to assess the effectiveness of these schemes.

Cost-effectiveness of the measures that are rewarded

6.108 The cost-effectiveness potential of policy instruments can be read from the marginal abatement cost curve (Figure 6.3), which shows how much reduction can be achieved at which costs per unit of reduction.

6.109 It can be seen from Figure 6.3 that, for most emission-reduction targets, policies that allow operational measures to be taken are more cost-effective than policies that allow only technical measures to be taken. Figure 6.3 shows, based on the analysis of the cost-effectiveness presented in Appendix 4, that voyage and operational options, coating and maintenance of the hull and maintenance of the propeller are cost-effective measures that would be incentivized by operational and market-based policy instruments but not by technical policy instruments.

6.110 It has to be noted, however, that marginal abatement cost curves, such as the one presented in Figure 6.3, are abstractions from reality. The marginal abatement cost curves shown in this report show fleet average cost-effectiveness, i.e. the net costs if a measure were applied to all ship types to which it can be applied. In reality, the cost-effectiveness of abatement measures will depend on the specific characteristics of ships and the way in which they are operated. Hence, measures that are shown to be cost-effective, on average, for the fleet may not be cost-effective for some ships while they are very cost-effective for others. Conversely, measures that are shown to be costly, on average, for the fleet may still be cost-effective for some ships. Market-based instruments allow each ship to find the optimal strategy that comprises taking all of the abatement measures that are cost-effective at a certain incentive level and buying allowances or paying a levy for the remaining emissions.

6.111 In comparing the cost-effectiveness of market-based instruments, the main difference is the impact of the price volatility. A fixed levy, such as used in the ICF, provides investors with more certainty about the returns on their investments than a METS, where prices of allowances are likely to be volatile. In general, uncertainty may result in postponement of investments, thus reducing the cost-effectiveness. In this case, however, the returns on an investment are the sum of the savings in fuel that is used and the lower emissions. The price volatility of fuel is not affected by the choice of instrument. Even assuming a relatively low fuel price of US$250 per tonne and a relatively high emission tax or allowance price of US$30 per tonne, the value of the emissions represents about one quarter of the total returns on the investment. This suggests that the additional impact of the choice of instrument on uncertainty will remain limited as long as fuel prices remain as volatile as the prices of emission allowances.

6.112 In summary, an analysis of the cost-effectiveness of measures that can be used for compliance with different policy instruments leads to the following conclusions:

1. as all conceivable emission-reduction measures can be used in market-based instruments, including emission reductions in other sectors, and as each actor that is affected by market-based instruments can find its optimal level of reduction of emissions, the cost-effectiveness of market-based instruments is very good;
2. as all conceivable emission-reduction measures can be used in operational policy instruments that are based on the EEOI, their cost-effectiveness is good; and
3. as only a subset of all conceivable emission-reduction measures can be used in technical policy instruments that are based on the EEDI, the cost-effectiveness of these policy instruments is moderate.

Administrative costs

6.113 According to a broad definition, "transaction costs" include all costs other than the costs of abatement (related to technical or operational measures) which are borne by the project proponent and the units that are responsible for implementing the scheme (Betz, 2007 [14]). Transaction costs can be divided into two categories:

1. costs for the market participants to comply with the rules of the scheme; and
2. costs of administration of the scheme.

This section focuses exclusively on mandatory policy instruments. The reason is not that voluntary agreements have low transaction costs – the empirical evidence suggests the contrary (OECD 2003 [9]). Rather, since the administrative arrangement of a voluntary agreement would be subject to negotiations between the parties to the agreement, little can be said *ex ante* about its costs. Conversely, the need to enforce mandatory policy instruments requires a minimum amount of administration, which can be assessed *ex ante*.

6.114 Based on the design of the policy instruments in paragraphs 6.48 to 6.71, the administrative tasks that are shown in Table 6.4 can be identified.

6.115 From Table 6.4, it is clear that the technical policy options have few administrative tasks. The EEDI has to be calculated once for each ship. The costs of this calculation appear to be limited, as all of the factors that are necessary for the calculation are in the design specifications. These costs can then be amortized over the life of a ship.

6.116 The administrative burden of operational policy instruments that are based on the EEOI is larger than the burden of technical policy instruments, since the EEOI has to be calculated annually or as a rolling average. Trials with the indicator suggest that most ship operators have the necessary data in their management information systems (CE Delft *et al.*, 2006 [5]). However, in a mandatory instrument, these data and the resulting EEOI would have to be verified periodically, e.g., annually, which would increase the costs.

6.117 Market-based instruments share many administrative burdens with the operational policy instruments that are based on the EEOI, as emissions have to be monitored, verified and reported annually. However, in contrast to the EEOI, it is not necessary to monitor and verify transport performance. In addition, there are costs associated with making the financial transaction or surrendering the allowances. Moreover, the administrative burden for the flag State and/or other organizations appears to be larger than that of other policy instruments.

Summary and conclusion on cost-effectiveness

6.118 This section has assessed the impact of two factors on the cost-effectiveness of policy instruments:

1. the costs of the emission-reduction measures; and
2. the administrative costs related to the implementation and the operation of the policy scheme.

The relative weight of these two factors in the overall cost-effectiveness depends on the overall environmental effect of the policy. If a policy is designed to yield a large environmental effect (e.g., if the levy is high, the emissions cap is tight, the EEDI or the EEOI target is far below the baseline), then actors will have to implement many costly emission-reduction measures to achieve this effect. In this case, the share of the administrative costs in the total costs will be low. Conversely, if the environmental effect is small, the administrative costs will be a large share of the total costs.

6.119 Table 6.5 presents a summary of the conclusions on each of these factors for the policy instruments that are discussed in the section.

6.120 In general, it is concluded that:

1. For policy instruments that are designed to have a large effect, the costs of abatement measures constitute a large share of the total costs. When these costs dominate, market-based policy instruments show a very good cost-effectiveness, as they allow operators to find the optimal level of abatement.
2. For policy instruments that are designed to have a small effect, the administrative costs are a larger share of the total costs. When these costs dominate, technical policy instruments show a very good cost-effectiveness, as they can be relatively easily monitored, reported and verified.

Table 6.4 *Administrative tasks in different policy instruments*

	Ship	Flag State	Port State	Other organizations
Mandatory EEDI limit value	Calculate EEDI. Have EEDI verified. Report EEDI.	Register ship's EEDI	Inspect ship's EEDI	IMO to establish a formula. IMO to set baseline and reduction target.
Mandatory EEDI reporting	Calculate EEDI. Have EEDI verified. Report EEDI.	Register ship's EEDI	Inspect ship's EEDI	IMO to establish a formula
Voluntary EEDI reporting	Calculate EEDI. Have EEDI verified. Report EEDI. (all on a voluntary basis)			IMO to establish a formula
Mandatory EEOI reporting	Calculate EEOI annually. Have EEOI verified annually. Report EEOI annually.	Register ship's EEOI	Inspect ship's EEOI	IMO to set baseline and reduction target
Mandatory use of SEMP	Draft SEMP	Register and verify whether ship has a SEMP	Inspect whether ship has a SEMP	IMO to establish SEMP guidelines
Mandatory EEOI limit value	Calculate EEOI annually. Have EEOI verified annually. Report EEOI annually.	Register ship's EEOI	Inspect ship's EEOI	IMO to set baseline and reduction target
Voluntary EEOI reporting	Calculate EEOI annually. Have EEOI verified annually. Report EEOI annually. (all on a voluntary basis)			IMO to maintain register
Voluntary use of SEMP	Draft SEMP on a voluntary basis			IMO to establish SEMP guidelines
METS	Monitor emissions and/or fuel use. Verify emissions and/or fuel use. Report emissions and/or fuel use. Acquire allowances. Surrender allowances.	Manage allowance registries for ships. Monitor compliance. Receive emission allowances.	Inspect proof of surrender of allowances	International organization to set a cap. International organization to allocate allowances. International organization to manage the fund.
ICF*	Monitor emissions and/or fuel use. Verify emissions and/or fuel use. Report emissions and/or fuel use. Pay levy.	Collect levy	Inspect proof of payment of levy	International organization to maintain a register of payments of levy. International organization to manage the fund.

* For the ICF, the administrative responsibilities of a ship could be transferred to the supplier of the bunker fuel, depending on the exact design of the policy (see paragraphs 6.68 and 6.69).

Incentives to technological change

6.121 This section relates to the criteria agreed by MEPC 57, that the policies should be supportive of promoting and facilitating technical innovation and R&D in the entire shipping sector and accommodating to leading technologies in the field of energy efficiency. This section analyses the incentives of policies for technological change.

6.122 Policies that increase the price of emitting CO_2 incentivize the implementation of technologies to reduce emissions just in the same way as high fuel prices incentivize the implementation of these

Table 6.5 *Summary assessment of the cost-effectiveness of policies*

Evaluation criteria	Technical policy options	Operational policy options				Market-based instruments	
	Mandatory EEDI limit for new ships	**Mandatory SEMP**	**Voluntary SEMP**	**Mandatory EEOI reporting**	**Mandatory EEOI limit**	**METS**	**International Compensation Fund**
Cost-effectiveness of the emission-reduction measures	Moderate, as only a subset of all conceivable emission-reduction options can be used	n.a.	n.a.	n.a.	Good, as all conceivable emission-reduction measures can be used	Very good, as all conceivable emission-reduction measures can be used, including measures in other sectors, and the market allows actors to find the optimal abatement level	Very good, as all conceivable emission-reduction measures can be used, including measures in other sectors, and the market allows actors to find the optimal abatement level
Administrative costs	Low, as EEDI needs to be calculated once in the lifetime of a ship			High, as EEOI needs to be calculated annually	High, as EEOI needs to be calculated annually	High, as emissions needs to be monitored, verified and reported annually and allowances have to be surrendered annually	High, as emissions needs to be monitored, verified and reported annually and financial transactions have to be made at least annually

technologies. If the demand for these technologies increases, suppliers of these technologies will be driven to invest more in R&D by their expectations of higher returns (Baumol 2002 [11]). Not only market-based policies have these effects. Mandatory EEOI or EEDI limit values would increase demand for emission-reducing technologies if they require more than a business-as-usual improvement of efficiency.

6.123 In general, the higher the cost of pollution, the stronger the incentive to invest in R&D and innovation. For market-based instruments, this implies that higher levies or more ambitious caps favour innovation. For technical and operational measures, the reduction below the baseline determines the incentive. In contrast, voluntary policies and/or reporting requirements have little potential to increase demand for technologies or to incentivize R&D, since they would not reward reductions of emissions beyond the business-as-usual levels.

6.124 As stated in paragraphs 6.75 to 6.120, technical policy options only incentivize technical measures to reduce emissions. In its current form, the EEDI would reward more efficient engines and a more efficient hull form, for example, but would not reward increased brushing of the hull or the propeller. Hence the incentive for innovation would only be directed at these measures. In contrast, operational and market-based policies would incentivize operational innovations as well.

6.125 In summary, we find that:

1. market-based instruments provide incentives to innovation and R&D aimed at improving the efficiency of ships by all technical and operational measures because they increase returns to innovations and R&D;
2. operational policy instruments provide incentives to innovation and R&D aimed at improving the efficiency of ships by technical and operational measures because they increase returns to innovations and R&D;
3. technical policy instruments provide incentives to innovation and R&D aimed at improving the technical efficiency of newly built ships by technical measures because they increase returns to innovations and R&D into these measures; and
4. voluntary policies provide weak incentives to R&D and innovation as they do not increase the returns.

Practical feasibility of implementation

6.126 This section relates to the criteria that were proposed by MEPC 57 that the GHG policy should be practical, transparent, fraud-free and easy to administer. Each of the policy options faces a number of technical, practical and legal issues. These may relate to the detailed design of the policy, the establishment of baselines, legal definitions, handling and enforcement as well as the possible need to establish new organizations/legal entities. It is acknowledged that many of these aspects depend on the details of the implementation as much as the principal policy designs. This is particularly the case for transparency and fraud. As such, these aspects cannot be assessed here.

6.127 The ease of administering a policy instrument depends on its administrative complexity. A measure for this, admittedly a rough one, is the number of tasks. Table 6.4 provides an overview of these. It shows that the market-based instruments are the most complex and the mandatory EEDI is the least complex instrument discussed here.

6.128 In terms of the issues that need to be resolved before the policy can be implemented, the following overview is based on Table 6.4:

1. A mandatory EEDI limit value will require the establishment of a baseline and a reduction target; paragraphs 6.15 to 6.23 and 6.49 to 6.54 provide examples of baselines. On this basis, it can be concluded that the establishment of a baseline is feasible. The establishment of a reduction target would probably require additional studies on the potential to improve the EEDI.
2. A mandatory EEOI limit value will require the establishment of a baseline and a reduction target; as indicated in paragraphs 6.24 to 6.27, the available data on the EEOI appear to indicate that baselines are variable, depending on the business cycle. Hence, it may be challenging to establish a baseline. For the same reason, establishing a reduction target may be challenging.

3. A mandatory or voluntary SEMP requires the establishment of guidelines for the SEMP. This seems to be rather unproblematic.
4. The METS would require the establishment of a cap, the allocation of allowances, the establishment of a registry and potentially the creation and management of a fund. As discussed in paragraphs 6.7 to 6.12, the establishment of a cap would probably require the collection of emission data or the improvement of current estimates. The other issues would require the creation of one or more organizations to be charged with these tasks. As all of these tasks have been carried out before for other sectors, they appear to be feasible, in principle.
5. The ICF would require the creation of one or more organizations that would maintain a registry of payments and manage the fund. As all of these tasks have been carried out before for other sectors, they appear to be feasible, in principle.
6. Both the ICF and the METS require international organizations to extend the scope of their work. It may be challenging to do so.

Summary assessment of policies

6.129 This section provides a summary table of the policy assessment from the previous sections. The purpose is to provide an overview of principal strengths and weaknesses of the various proposals under consideration by the MEPC. Note that such a table is necessarily a simplification of the assessments that have been carried out. Therefore, the reader is strongly urged to use this table only in connection with the more elaborate assessments in the previous sections.

6.130 The table applies to policy instruments that go beyond a reporting requirement. The reason is that the effectiveness and cost-effectiveness of reporting instruments depends on the use that is being made of the reported data in other policies, such as, for example, a scheme of differentiated harbour dues or labelling. It is beyond the scope of this study to assess the effectiveness of these schemes.

Table 6.6 *Summary assessment of policies, based on condensed criteria**

Evaluation criteria*	Technical policy options	Operational policy options			Market-based instruments	
	Mandatory EEDI limit for new ships	Mandatory SEMP	Voluntary SEMP	Mandatory EEOI limit	METS	International GHG Fund
Environmental effectiveness	Long-term: moderate	Low	Low	High	Very high	Very high
Cost-effectiveness	Moderate	Unclear	Unclear	Good	Very good	Very good
Incentive to technological change	High, but limited to technical measures	Low	Low	High	High	High
Practical feasibility of implementation	High	High	High	Low	Moderate	Moderate

* The relation between these four criteria and MEPC 57 is explained in paragraphs 6.72 to 6.74.

CONCLUSIONS

6.131 Results from chapter 7 (Scenarios for future emissions from shipping) and Chapter 8 (Climate impacts) of this study indicate that reductions in future emissions from shipping are needed beyond what can be achieved in "business as usual" scenarios. Chapter 5 provides examples of technical and operational measures that can be taken to reduce emissions. As some of these measures are costly, policies will be needed to support their implementation. This chapter analyses policy options to reduce emissions of CO_2 from ships in this context. Particular attention is paid to policy options that have been discussed within IMO. It is presently not possible to make a quantitative assessment of the effect of these policies. However, the following qualitative conclusions can be drawn.

1. A mandatory EEDI limit for new ships appears to be a cost-effective solution that can provide a strong incentive to reduce emissions from new ships. The primary limitation of the EEDI is that it

only addresses ship design; operational measures are not considered. The effect is also limited, in the sense that it applies only to new ships. Because of these two factors, the effectiveness and the cost-effectiveness of a mandatory EEDI limit as an instrument to reduce global CO_2 emissions are limited.

2. A mandatory EEOI limit appears to be a cost-effective solution that can provide a strong incentive to reduce emissions from all ships engaged in transport work. It incentivizes both technical and operational measures. However, implementing this option is technically very challenging, due to the difficulties in establishing and updating baselines for operational efficiency and in setting targets.
3. Mandatory EEOI recording/reporting upon request appears to be a practically feasible option. The environmental effectiveness and the cost-effectiveness are difficult to assess since the reductions that may be achieved depend on incentive schemes being set up to make use of the information.
4. Voluntary use of a SEMP appears to be a feasible approach to increase awareness of cost-effective measures to reduce emissions. However, since this instrument does not require a reduction of emissions, its effectiveness will depend on the availability of cost-effective measures to reduce emissions (i.e. measures for which the fuel savings exceed the capital and operational expenditures). Likewise, it will not incentivize innovation and R&D beyond the "business as usual" situation.
5. Mandatory use of a SEMP would increase the scope of application as compared to the voluntary use of a SEMP; however, the incentive to reduce emissions remains unchanged.
6. Both METS and the ICF appear to be cost-effective policy instruments with high environmental effectiveness. They have the largest amount of emissions within their scope, allow all measures in the shipping sector to be used and can offset emissions in other sectors. As market-based instruments, they are considered cost-effective. Both require setting up new institutions or extending the scope of existing ones, which may be challenging.
7. The environmental effect of the METS is an integral part of its design and will therefore be met. In contrast, part of the environmental effect of the ICF depends on decisions about the share of funds spent on buying emission allowances from other sectors. With regards to cost-effectiveness, incentives to technological change and feasibility of implementation, both policy instruments seem to be quite similar.

REFERENCES

1 "Draft interim guidelines on the method of calculation of the energy efficiency design index for new ships" (Report of the Marine Environment Protection Committee on its fifty-eighth session). IMO document MEPC 58/23, annex 11.
2 DNV Technical Report 2007–1891 rev 3. Submitted to IMO as document MEPC 57/INF.12.
3 "Methodology for Design CO_2 Index baselines and recalculation thereof". IMO document MEPC 58/4/8.
4 Anink, D. and Krikke, M. 2009. "The IMO Energy Efficiency Design Index: A Netherlands Trend Study", CMTI Centre for Maritime Technology and Innovation, 7 January 2009.
5 CE Delft, MARINTEK, DNV and Germanischer Lloyd. 2006. "Greenhouse Gas Emissions for Shipping and Implementation Guidance for the Marine Fuel Sulphur Directive", Delft, http://ec.europa.eu/environment/air/pdf/transport/final_report.pdf
6 "Ship emission indexing in a logistic chain perspective". Annex to IMO document MEPC 55/4/4.
7 "Ship Efficiency Management Plan". Submitted to IMO by ICS, Bimco, Intercargo, Intertanko, and OCIMF as document MEPC 58/INF.7.
8 Sorrell, S. 2007. *The Rebound Effect: an assessment of the evidence for economy-wide energy savings from improved energy efficiency*. UKERC, London, UK. ISBN 978-1-903144-03-9.
9 OECD. 2003. *Voluntary Approaches for Environmental Policy: Effectiveness, Efficiency and Usage in Policy Mixes*. ISBN 978-92-64-10178-4.
10 "Proposal for elements to be included in an IMO strategy on greenhouse gases", IMO document MEPC 49/4/5.
11 Baumol, W.J. 2002. *The Free-Market Innovation Machine – Analyzing the Growth Miracle of Capitalism*. Princeton University Press. ISBN 978-0-691-11630-3.
12 Bureau of Transport and Communications Economics. 1990. "Freight Flows in Australian Transport Corridors". Occasional Paper 98, Canberra, Australia.
13 Beuthe, M., Jourquin, B., Geerts, J.-F. and Koul à Ndjang'Ha, C. 2001. "Freight transport demand elasticities: A geographic multimodal transportation network analysis". *Transportation Research E*, 37: 253–266.
14 Betz, R. 2007. "Emissions trading to combat climate change: The impact of scheme design on transaction costs", Centre for Energy and Environmental Markets. University of New South Wales, Sydney, Australia.

15 Faber, J., Boon, B., Berk, M., den Elzen, M., Olivier, J. and Lee, D. 2007. "Aviation and maritime transport in a post-2012 climate policy regime", CE Delft, Delft.
16 Corbett, J.J., Winebrake, J.J., Green, E.H., Kasibhatla, P., Eyring, V. and Lauer, A. 2007. "Mortality from Ship Emissions: A Global Assessment", *Environmental Science & Technology*, 41: 8512–8518.
17 ExternE, 2005. "ExternE, Externalities of Energy, Methodology 2005 update", ed. Bickel, P. and Friedrich, R. European Commission DG for Research, Sustainable Energy Systems. http://www.externe.info/brussels/methup05a.pdf accessed on 20 December 2008
18 Hanley, N., Shogren, J.F. and White, B. 1997. *Environmental Economics in Theory and Practice*, Oxford University Press, New York.
19 Hein, L. and Blok, K. 1995. "Transaction costs of energy efficiency improvement" in Proceedings of the 1995 Summer Study: Sustainability and the Reinvention of the Government – A Challenge for Energy Efficiency, ed. Persson, A. The European Council for an Energy Efficient Economy, Stockholm (NWS-95056).
20 IPCC. 2007. Climate Change 2007: Synthesis Report. Contribution of Working Groups I, II and III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, Pachauri, R.K and Reisinger, A. (eds.)]. IPCC, Geneva, Switzerland, 104 pp.
21 Kågeson, P. 2007. "Linking CO_2 Emissions from International Shipping to the EU ETS". Report commissioned by the Federal Environment Agency, Germany, July 2007.
22 Marbek Resource Consultants, PricewaterhouseCoopers; International Institute for Sustainable Development, 2004, "Administration and transaction cost estimates for a greenhouse gas offset system", final report, in Betz, R. 2007. "Emissions trading to combat climate change: The impact of scheme design on transaction costs".
23 Meyrick and Associates, GHD and Booz Allen Hamilton. 2007. "International and Domestic Shipping and Ports Study". Wollongong, Australia.
24 Preiss, P., Friedrich, R. and Klotz, V. 2008. "Report on the procedure and data to generate averaged/aggregated data", deliverable No. 1.1 – RS 3a, NEEDS integrated project.
25 Oum, T.H., Waters, W.G. and Yong, J.S. 1990. "A survey of recent estimates of price elasticities of demand for transport". Infrastructure and Urban Development Department, The World Bank, Policy Research Working Paper number 359.
26 Russell, C.S. and Powell, P.T. 1999. "Practical considerations and comparison of instruments of environmental policy", in *Handbook of Environmental and Resource Economics*, ed. J.C.J.M. van den Bergh. Edward Elgar Publishing Ltd., Cheltenham, UK.
27 Skjølsvik, K.O., Andersen, A.B., Corbett, J.J. and Skjelvik, J.M., 2000. "Study of greenhouse gas emissions from ships" (MEPC 45/8: Report to International Maritime Organization on the outcome of the IMO Study on Greenhouse Gas Emissions from Ships). MARINTEK Sintef Group, Carnegie Mellon University, Center for Economic Analysis, and Det Norske Veritas: Trondheim, Norway.
28 Stern, N. 2006. "Stern Review report on the economics of climate change" http://www.hm-treasury.gov.uk/stern_review_report.htm accessed on 15 January 2009.
29 Torvanger, A., Bogstrand, B., Bieltvedt Skeie, R. and Fuglestvedt, J.S. 2007. "Climate regulation of ships", CICERO Report 2007:7.
30 Tol, R.S.J. 2007. "The Social Cost of Carbon: Trends, Outliers and Catastrophes", Economic Discussion Paper 2007–44 http://www.economics-ejournal.org/economics/discussionpapers/2007–44, accessed on 15 January 2009.
31 Tietenberg, T.H. 2006. "Emissions Trading. Principles and Practice". Resources for the Future, Washington D.C., USA.
32 Varian, H.R. 2005. *Intermediate Microeconomics*, 7th international student edition, W. W. Norton & Company Inc., New York, USA.
33 Zylicz, T. 2004. "Ekonomia srodowiska i zasobow naturalnych" (*Economics of the environment and natural resources*), Polish Economic Press, Warsaw. ISBN 83-208-1521-5 (978-83-208-1521-4).

7

Scenarios for future emissions from international shipping

INTRODUCTION

7.1 This chapter presents future scenarios that affect emissions from international shipping. The scenarios are primarily based on assumptions of global development in the Intergovernmental Panel on Climate Change (IPCC) SRES storylines (Nakicenovic *et al.*, 2000 [6]). Principally, the scenarios that were developed within this project can be considered as a detailing of shipping and seaborne trade within possible futures outlined by IPCC SRES scenarios. In developing these scenarios, the research team interpreted the phrase "different regulatory Scenarios" that is mentioned in 1.3 of the Terms of Reference for phase 1as no *explicit* regulatory policy or mandates requiring the mitigation of CO_2 from shipping; as such, the scenarios are used to help identify important economic, technological, and operational variables affecting future emissions. Naturally, differences in technology (ship efficiency and fuel type) can be seen as the effects of *implicit* policies. In the case of other pollutants, the revised MARPOL Annex VI is assumed to apply.

7.2 The chapter identifies three key driving variables that will affect ship emissions up to the year 2050. These variables fall into the following categories: (1) economy; (2) transport efficiency; and (3) energy. The values for the key parameters in each of these four categories were generated using an "open Delphi process" based on expert opinion and analysis. Developed at the Rand Corporation in the 1960s, this process allows for diverse expert groups to rely upon their best sources of information for each parameter without explicitly compromising or agreeing on their differences [22]. We then applied these values to a model of global fleet emissions inventory that was calibrated to the inventory model that has been discussed in the previous chapters. Altogether we modelled and analysed 324 scenarios (a set of 162 for 2020 and a set of 162 for 2050). The results of this analysis provide a range of possible future emissions from shipping up to the year 2050.

IPCC SRES SCENARIOS

7.3 Scenario planning is a common tool for researchers evaluating uncertain futures. Some of the definitions of scenario planning, include [1]:

1. "[An] internally consistent view of what the future might turn out to be – not a forecast, but one possible future outcome" [2].
2. "[A] tool for ordering one's perceptions about alternative future environments in which one's decisions might be played out" [3].
3. "[A] disciplined methodology for imagining possible futures in which organizational decisions may be played out" [4].

Scenarios help us envision a future in order to develop robust decisions and test how these decisions play out in possible future worlds [5]. In this chapter, scenarios are used to provide a range of possible future emissions in order to help decision makers think strategically about the options for reducing such emissions.

7.4 In 1992, the IPCC began to develop a set of emissions scenarios that would provide both a contextual setting and emissions data for their climate models. These scenarios build on a baseline estimate

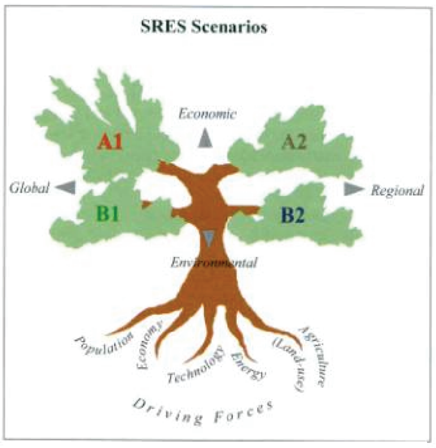


Figure 7.1 *IPCC Storylines (IPCC).*

of emissions and then explore different rates of technological change, economic growth, and demographic trends [6]. For the most part, these scenarios were updated in 2000 for the Third Assessment Report, and more recently in 2007 for the Fourth Assessment Report and the IPCC Special Report on Emissions Scenarios (SRES) [7]. The IPCC uses the following terminology for its scenarios [8]:

> "Storyline: a narrative description of a scenario (or a family of scenarios), highlighting the main scenario characteristics and dynamics, and the relationships between key driving forces.
>
> Scenario: projections of a potential future, based on a clear logic and a quantified storyline.
>
> Scenario family: one or more scenarios that have the same demographic, politico-societal, economic and technological storyline."

7.5 Figure 7.1 shows the different storylines that have been developed in the SRES. These are labelled A1, A2, B1 and B2. The driving forces are shown in this figure to include: *Population, Economy, Technology, Energy, Land-Use, and Agriculture*. These driving forces are evaluated against two major tendencies: (1) globalization versus regionalization; and (2) environmental values versus economic values. Below is a summary of each storyline, taken from IPCC documentation (noting that each storyline includes a variety of individual scenarios) [6, 7]:

1. *Storyline A1:* a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and rapid introduction of new and more efficient technologies. Major underlying themes are economic and cultural convergence and capacity building, with a substantial reduction in regional differences in per capita income. In this world, people pursue personal wealth rather than environmental quality.
2. *Storyline A2:* a very heterogeneous world with continuously increasing global population and regionally oriented economic growth that is more fragmented and slower than in other storylines.
3. *Storyline B1:* a convergent world with the same global population as in the A1 storyline but with rapid changes in economic structures toward a service and information economy, with reductions in material intensity, and the introduction of clean and resource-efficient technologies.
4. *Storyline B2:* a world in which the emphasis is on local solutions to economic, social, and environmental sustainability, with continuously increasing population (lower than A2) and intermediate economic development.

7.6 The IPCC used these storylines to project values for the different driving factors, resulting in a set of 40 scenarios, developed by six modelling teams. The IPCC did not apply probabilities to these scenarios. Six groups of scenarios were taken from the four storylines: one group each in the A2, B1 and B2 families, and three groups in the A1 family. The three A1 scenarios were used to characterize future energy use as follows: A1FI (fossil-intensive), A1T (technologically advanced and predominantly non-fossil) and A1B (balanced across energy sources).

7.7 The identification of key driving variables for the IPCC work relied on relationships that are best exhibited in the IPAT model of environmental impact and its related model for CO_2 emissions, shown below:

$$\text{Impact} = \text{Population} \times \text{Affluence} \times \text{Technology}$$

$$CO_2 \text{ Emissions} = \text{Population} \times (\text{GDP/Population}) \times (\text{Energy/GDP}) \times (CO_2/\text{Energy})$$

Although simple, the IPAT model demonstrates the important relationships of four of the key driving factors mentioned above: population, economics, technology, and energy. The final data tables for each of the 40 IPCC scenarios can be found at: http://sres.ciesin.org/final_data.html.

METHODOLOGY

7.8 This project takes a similar approach to the IPCC in developing scenarios for analysis. Using Schwartz's methodology for construction of scenarios [9], we identified key driving variables that would affect emissions from ships into the future. These variables can be placed into three primary categories, as shown in Table 7.1. This table also shows some of the related elements that might affect the future value of each variable.

Table 7.1 *The driving variables that are used for scenario analysis*

Category	Variable	Related elements
Economy	Shipping transport demand (tonne-miles/year)	Population, global and regional economic growth, modal shifts, sectoral demand shifts
Transport efficiency	Transport efficiency (MJ/tonne-mile) – depends on fleet composition, ship technology and operation	Ship design, propulsion advancements, vessel speed, regulation aimed at achieving other objectives but that have a consequence for GHG emissions
Energy	Shipping fuel carbon fraction (g of C/MJ of fuel energy)	Cost and availability of fuels (e.g., use of residual fuel, distillates, biofuels, or other fuels)

7.9 In this study, carbon emissions are explicitly modelled as a parameter of the scenario. Calculations of levels of emission of other pollutants are based on energy consumption and MARPOL regulations. Individual technology scenarios for reduction of other pollutants have not been developed.

7.10 These driving factors affect various categories of ships in different ways. Therefore, the international shipping fleet was separated into three primary categories to allow differentiation of the overall effects of the above factors. These categories are:

1. Coastwise shipping – ships used in regional (short-sea) shipping; mostly small ships and RoPax vessels;
2. Ocean-going shipping – larger ships suitable for intercontinental trade; and,
3. Container ships (all sizes).

This categorization allows modelling of different growth rates, efficiencies and fuel use for the various scenarios. The split between large and small ships is generally set at about 15,000 dwt; hence the vast majority of the non-containerized fleet is considered to be ocean-going shipping. Although small container feeder vessels could be considered to be short-sea vessels, the demand for container feeders is linked with the demand for container transport in general. Thus it was decided to include all pure container-ships in a single category.

7.11 Based on this categorization, we estimated values for each variable with respect to each of the IPCC scenario families (i.e. A1FI, A1B, A1T, A2, B1, and B2). These values were generated using an "open Delphi approach", which relies on shared expert opinion interspersed with "rounds" of reflection and discussion. In this case, the project team, made up of shipping experts from around the globe, met in Munich, Germany for a three-day workshop (5–7 March 2008) to discuss each variable, the elements that affect the value for each variable, and the role the variable would play in the overall scenario logics. During this workshop, the initial parametric values for each variable were generated through a process of discussion and debate. Following this workshop, further refinements of estimates of variables and the design of the scenario model were made through electronic means and via an electronic web-based meeting of the project team on 25 April 2008 and other conference calls throughout May 2008. Parameterization of the scenario was finalized in a team workshop, held in London on 3–4 June 2008.

INPUT VALUES FOR SCENARIO MODELLING

Economic growth and growth in seaborne transport

7.12 Demand for transport governs the size and activity level of the world fleet and is the most important driver for emissions from ships. Future demand for transport will depend on developments in trade, locations of factories, consumption of raw materials, changing trade patterns, possible new sea routes, etc. Emissions from ships are also sensitive to the freight market in the sense that, when demand for transport for a cargo type is low compared to the number of ships in this market, reductions of speed will be encouraged and efficiency of transport may increase. Conversely, when there is a relative shortage of ships, they will be operated at higher speeds, resulting in lower efficiency and more emissions. This type of market instability is not modelled. Instead, the scenario model projects future transport demand based on expectations for economic growth; also, the future fleet is assumed to grow at an idealized rate in order to meet future demands for transport.

7.13 Historically, there is a strong link between economic growth and an increase in shipping. This relationship has been used in previous studies to estimate future demand for transport [11]. Given the complexity of the problem and the strong historical link between GDP and shipping, the use of the historic relationships is not an unreasonable approach. However, this approach cannot account for other trends that may be important. The Ocean Policy Research Foundation (OPRF) has recently reported the results from a fundamental study of future seaborne trade, based on the IPCC A1B scenario [21]. A brief review and the results of these two approaches are now given.

Estimates of demand for transport from historic correlation with GDP

7.14 A historic correlation between global GDP and demand for sea transport is given in [11]. Based on this correlation, estimates for future tonne-mile demand were made for each of the scenarios. Since our scenario model distinguishes between ocean-going shipping, coastwise shipping and container shipping, the projections of tonne-miles must be divided between the modes. This split has been made after considering the regional emphasis of the various SRES scenarios and the strong growth in container traffic. During the past 20 years, container transport has grown nearly 10% annually [10]. This trend cannot be assumed to continue to 2050, since container transport would then in itself exceed the projected tonne-mile levels for world seaborne trade. Instead, it is assumed that the average growth of containerized transport is 2 percentage points higher than that of other cargo types. This results in 55% of the global tonne-miles being attributed to containers, as opposed to 24% in 2007. Projections for 2020 were exponentially interpolated from the scenario for 2050. The resulting input values for the scenarios are given in Table 7.2. This table shows future tonne-miles on an index relative to 2007 for each family of scenarios. For instance, a figure of 320 for ocean-going shipping in the 2050 A1B scenario family means that the total number of tonne-miles of work done by ocean-going shipping in 2050 is 3.2-times larger than in 2007.

Table 7.2 *Tonne-mile index (2007 = 100) for 2050 from correlation with GDP*

2050	A1B	A1F	A1T	A2	B1	B2
Ocean-going shipping	320	320	320	240	220	180
Coastwise shipping	320	320	320	270	220	220
Container	1,230	1,230	1,230	960	850	690
Average, all ships	540	540	540	421	372	302

Scenarios for transport demand building on the OPRF A1B scenario

7.15 The OPRF in Japan is currently undertaking a major study in which the demand for transport, in tonne-miles, is projected towards 2050, based on the IPCC A1B scenario. In this interesting and detailed scenario, the OPRF applies the correlation between GDP and tonne-miles to the transport of containers only. For other cargo (such as dry bulk, crude oil, LNG and petroleum production), the OPRF uses different parameters, such as total population and primary energy use. These parameters are also estimated by the IPCC; however, their rate of increase is lower than that of GDP. Therefore, the resulting projection of the demand for transport is lower than if GDP was used on all rates. Secondly, the OPRF also foresees changes in the average distance of transportation, due to changes in the transport patterns and modal shifts. Amongst the significant future developments that are anticipated by the OPRF are the widening of the Panama Canal and the commissioning of new gas pipelines from Myanmar to China (2030s), from the Middle East to India (2030s), and from Russia to China (2010s). It is also anticipated that the pipeline from North Africa to Europe is expanded (2030s), and that the modernization of the Siberian railroad is completed (2030s). This railroad will carry a share of the container traffic from East Asia to Europe. It is also anticipated that the Arctic sea route between East Asia and Europe will be commercially attractive (2040s). Work presently being undertaken within IMO with respect to ensuring safe navigation of ships and the prevention of pollution in polar waters (the development of the Polar Code) will be critical to facilitate this change. Moreover, increased recycling of scrap iron from 2020 to 2050 will be the equivalent of a reduction of approximately 5% in the production of iron ore. Altogether, OPRF estimates a transport demand for A1B in 2050 that is about half of what is estimated by analysis of trends in GDP.

7.16 Demand for transport is estimated for a broad range of ship types in the OPRF scenario. These ship types are aggregated into the relevant categories that are needed for the scenario and the A1B tonne-mile projection was given for our A1B family. For our other families of scenario, judgements were made regarding the relative developments in the scenarios with regards to regionalization, growth in GDP and other aspects of the scenario compared with A1B to produce the scenarios below. It is stressed that, while A1B is the product of a detailed analysis, the others are not. Projections for 2020 were exponentially interpolated from the scenario for 2050. The resulting scenarios are given in Table 7.3.

Table 7.3 *Tonne-miles, building on the OPRF detailed A1B 2050 scenario (2007 = 100)*

2050	A1B	A1F	A1T	A2	B1	B2
Ocean-going shipping	170	170	170	140	150	130
Coastwise shipping	170	170	170	160	150	150
Container	570	570	570	330	380	360
Average, all ships	266	266	266	188	205	187

Projections of tonne-mile that are used in this study

7.17 Acknowledging the uncertainties with each of the two above-mentioned approaches, it was agreed that the average of these two approaches should be used. This average would encapsulate both the historic relationship and aspects of an analysis of future trends, including changes in trade patterns, the possible opening of Arctic sea routes, etc. At the same time, it was agreed to construct upper and lower bounds for the scenario that were wide enough to cover estimates from both approaches with a reasonable margin. The relationship between these figures is shown schematically in Figure 7.2. The resulting projections of tonne-miles, summarized in Table 7.4, Table 7.5 and Table 7.6, were selected for use in this study.

Transport efficiency

7.18 Measures that may be used to increase their energy efficiency and reduce the emissions of CO_2 from ships are described in Chapter 5 and Appendix 2 to this report. Chapter 5 also presents an assessment of the potential for reduction of CO_2 emissions. In this section, scenarios are presented for the future efficiency of transport.

7.19 Shipping has a long history of increasing efficiency. For a given ship size, speed is the most critical defining parameter with respect to fuel consumption. A certain speed is typically associated with "standard" ship operating patterns. Typically, the shipowner will order a ship that has a certain speed reserve, to give the vessel limited additional speed flexibility, which may be very valuable on certain occasions (such as canal and harbour slots, or when freight rates are high). This also gives the world fleet a degree of flexibility to handle fluctuations in demand for transport services. Over time, technological developments

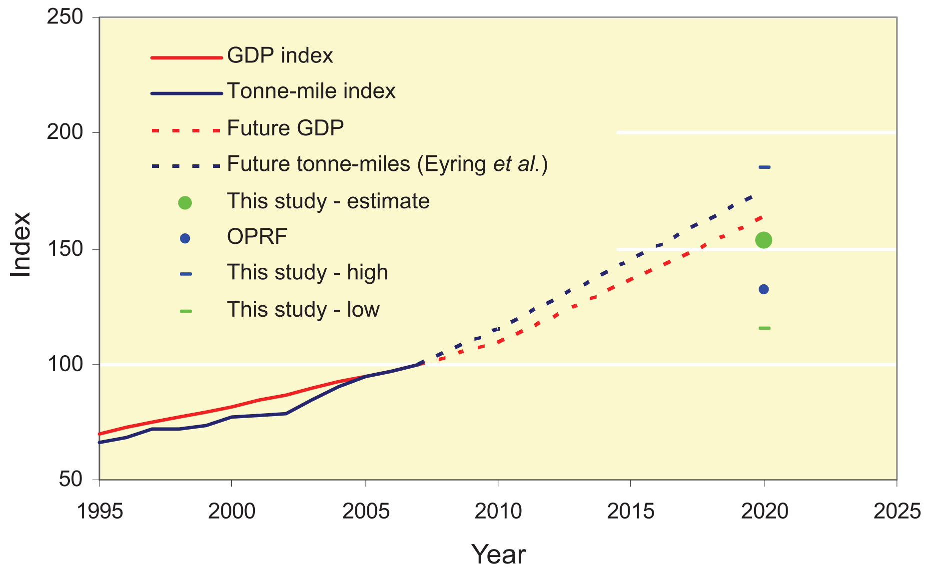


Figure 7.2 *Principles for the estimation of transport demand. For each of the scenarios, the demand for transport was estimated from SRES expectations of GDP and (1) historic GDP correlation (blue dotted line), and (2) based on the OPRF forecast. The estimate that was used in this study is the average value, illustrated by the green dot. High and low values were respectively higher and lower than the results from the two approaches.*

Table 7.4 *Projections of tonne-miles used in this study (2007 = 100)*

	A1B	A1F	A1T	A2	B1	B2
2050						
Ocean-going shipping	245	245	245	190	185	155
Coastwise shipping	245	250	245	215	185	185
Container	900	875	905	645	615	525
Average, all ships	402	397	403	302	288	247
2020						
Ocean-going shipping	131	131	131	121	120	114
Coastwise shipping	131	132	131	126	120	120
Container	194	193	195	176	173	165
Average, all ships	146	146	146	135	133	127

Table 7.5 *Upper bound for projections of tonne-miles used in this study (2007 = 100)*

	A1B	A1F	A1T	A2	B1	B2
2050						
Ocean-going shipping	383	383	383	262	252	193
Coastwise shipping	383	395	383	315	252	252
Container	2,700	2,588	2,723	1,638	1,525	1,203
Average, all ships	939	913	945	597	558	441
2020						
Ocean-going shipping	150	150	150	134	132	122
Coastwise shipping	150	152	150	142	132	132
Container	271	267	272	233	228	212
Average, all ships	179	178	179	159	155	145

Table 7.6 *Lower bound for projections of tonne-miles used in this study (2007 = 100)*

	A1B	A1F	A1T	A2	B1	B2
2050						
Ocean-going shipping	157	157	157	138	136	124
Coastwise shipping	157	158	157	147	136	136
Container	300	296	301	254	248	229
Average, all ships	191	190	192	167	163	150
2020						
Ocean-going shipping	115	115	115	110	110	107
Coastwise shipping	115	115	115	112	110	110
Container	139	139	140	133	132	128
Average, all ships	121	121	121	116	115	112

Table 7.7 *Inputs to a scenario, summarized as annual growth rates*

		A1B	A1F	A1T	A2	B1	B2
GDP*		3.9%	4.0%	3.6%	2.4%	3.3%	2.7%
Total transport	Base	3.3%	3.3%	3.3%	2.6%	2.5%	2.1%
demand	High	5.3%	5.3%	5.4%	4.2%	4.1%	3.5%
	Low	1.5%	1.5%	1.5%	1.2%	1.1%	0.9%

* Annual average growth in world GDP for the period 2000 to 2050 [8].

have resulted in increased efficiency. Examples include the move from steam turbines to diesel engines and the subsequent improvements of these, better designs and optimization of hulls and of propellers with improved knowledge, manufacturing and analytical tools, and many other aspects. It should also be mentioned that the efficiency of ships today is a reflection of what has been perceived to be the economic optimum at the time of their design. In consideration of the above, when modelling future scenarios, we have decided to split the efficiency into three main elements:

1. Efficiency of scale, larger ships being more efficient (provided there is enough cargo to take advantage of the capacity offered);
2. Speed; and
3. Ship design and operation.

Efficiency of scale

7.20 When larger ships are added to replace smaller ships, this typically results in increased transport efficiency and vice versa. Effects of scale are implemented in the model of our scenario by way of changes to the composition of the future fleet. In this study, the composition of the fleet in 2020 was estimated by Lloyd's Register – Fairplay Research (LRFPR). This fleet projection is broadly similar to the estimate of the 2020 fleet given by the IMO group of experts [12]. The fleet in 2020 will have a certain nominal transport capacity. However, since the demand for transport in terms of tonne-miles is different in the various scenarios (see above), the estimate for the 2020 fleet must be scaled to fit the scenario in question. In order to do this, total gross tonnage was then used as an indicator for the transport work potential of each of the categories. The total gross tonnages for the 2007 fleet and the estimated 2020 fleet are shown in Table 7.8.

Table 7.8 *Total gross tonnage for fleet categories and growth index*

	2007	2020	Nominal GT index
Ocean-going shipping	536,731,017	954,049,435	178
Coastwise shipping	80,986,919	95,022,648	117
Container	126,217,091	348,078,393	276

7.21 Scaling factors for the scenario for specific fleet compositions were calculated by dividing the nominal GT index by the tonne-mile projection index given for each scenario. The following example illustrates the method: For 2020, according to the A1B scenario, the transport demand index for ocean-going shipping has increased to 131 while the projected fleet (expressed by the Nominal GT index) is 178 (Table 7.9). A scaling factor is then calculated to harmonize these. This factor is subsequently applied to the number of ships of each category for the scenario in question.

Table 7.9 *Calculation of scaling factor for 2020*

	A1B* (1)	Nominal GT index (2)	Scaling factor (2)/(1)
Ocean-going shipping	131	178	0.74
Coastwise shipping	131	117	1.12
Container	194	276	0.70

* Projected tonne-mile index.

7.22 The fleet for scenario A1B in 2020 is then estimated by multiplying the number of ships within each ship category in the *nominal* 2020 fleet by the appropriate scale factor. The overall approach to our calculation of the future fleet for 2020 is shown in Figure 7.3.

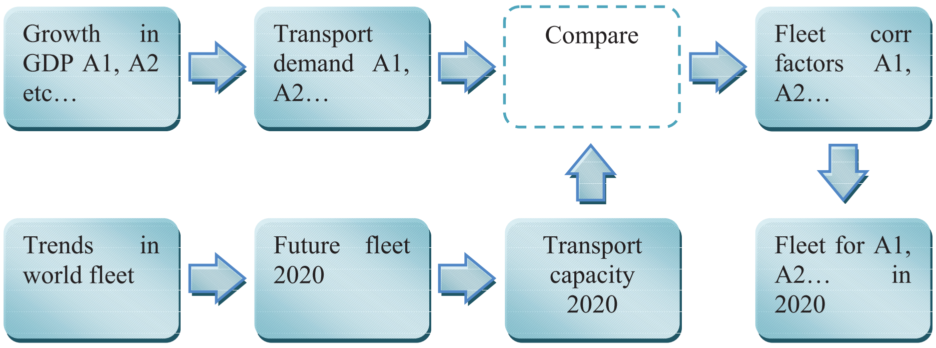


Figure 7.3 *Process for determining the future composition of the fleet in 2020*

7.23 Predicting a composition of the fleet in 2050 is significantly more challenging than predicting the composition of the fleet in 2020. For this reason, no structural change is modelled between 2020 and 2050. Instead, for 2050, we took the fleet structure in 2020 for each individual scenario and applied growth factors corresponding to the change in projected tonne-miles. Potential improvements in efficiency with changes to fleet structure in this period were considered in the subsequent assessment of efficiency. For instance, calculation of the growth factor for the A1B scenario between 2020 and 2050 is shown in Table 7.10.

Table 7.10 *Calculation of growth factor*

	A1B 2020*	A1B 2050*	Growth factor
Ocean-going shipping	131	245	1.87
Coastwise shipping	131	245	1.87
Container	194	900	4.64

* Projected tonne-mile index.

7.24 It should be noted that, in many cases, the number of ships expected in 2020 according to our scenarios is lower than what is projected by Lloyds Register – Fairplay Research. This is mainly a result of lower expectations for transport demand in our scenarios than what is predicted by Lloyds Register – Fairplay Research, whose prediction is not tied to SRES economic developments.

Speed

7.25 At lower speeds, frictional resistance of the hull predominates and the requirement for propulsion power is roughly proportional to the third power of speed. At higher speeds, resistance arising from the generation of waves becomes prominent, and this additional resistance makes the demand for power increase at more than the third power of speed. Therefore, reducing speed is an effective measure to reduce power consumption; particularly for faster ships. On the other hand, when there is a shortage of transport capacity and rates are high, increasing speed is a way of meeting the demand for transport capacity.

7.26 The speed of a vessel in operation will be determined by economic considerations, including freight rates, bunker prices, and other fixed and variable costs. For instance, in a situation where bunker prices are increasing and transport capacity grows faster than demand, market-driven reductions of operating speed may be expected. Changes of speed may thus be used to absorb market fluctuations and surplus of capacity. Also, in the long-term perspective, if fuel costs are expected to increase relative to other costs, the fleet may be expected to adapt by expanding in size and reducing the operational speed of each vessel, and vice versa.

7.27 The scenario model incorporates possible market-driven changes of speed, based on assumptions for 2020 and 2050 regarding the average speed of the fleet relative to the average speed of the current fleet. In Table 7.11, we set the lower bound of the change of speed to zero, indicating that average design speeds for the fleet would not change in future years. While past observations reveal increases in speed (e.g., during the rise of containerization), average speeds of fleets have stabilized to a large extent and, under anticipated market conditions that will consider energy and GHG performance, the team did not choose to model such a scenario. This set of values of speed reduction was used across all families of scenario.

Table 7.11 *Inputs to the scenarios: market-driven changes of average fleet speed*

	All scenarios		
	Base	**High**	**Low**
2050			
Intercontinental	−10%	−20%	0%
Coastwise shipping	−10%	−20%	0%
Container	−10%	−40%	0%
2020			
Intercontinental	−5%	−10%	0%
Coastwise shipping	−5%	−10%	0%
Container	−5%	−20%	0%

7.28 The net gain in efficiency resulting from the reduction in speed is modelled by assuming a third-power relationship between speed and power. Since changes to vessel speed affect the transport capacity of the ship, the model adjusts the fleet size in order to maintain a constant productivity of the fleet. As a simplification, the reduction of speed is also applied to auxiliary power, although this results in a slight over-estimation of the benefit. The net effect of reductions of speed and other measures is shown in Table 7.12.

Ship design, technology and operation

7.29 This assessment indicates the expected developments in technology within the various scenarios. Since there is no explicit regulation on consumption of fuel, the change in the technology factor reflects improvements that are cost-effective in the various scenarios rather than their full technological potential.

Table 7.12 *Inputs to the scenarios: market-driven changes in technology and regulatory side effects affecting efficiency of transport (fleet average values)*

	All scenario families		
	Base	**High**	**Low**
2050			
Ocean-going shipping	–25%	–35%	–5%
Coastwise shipping	–25%	–45%	–5%
Container	–25%	–30%	–5%
2020			
Ocean-going shipping	–2%	–4%	0%
Coastwise shipping	–2%	–4%	0%
Container	–2%	–4%	0%

7.30 Improvements in technology that have been considered in the discussion include:

- recovery of rotational energy (contra-rotating propellers, efficient rudders, asymmetric hulls, boss cap fins, etc.);
- general improvements to the hull and changing design priorities *except the use of larger ships*;
- improvements in engine technology;
- increased use of recovery of waste heat;
- operational improvements beyond the reductions in speed that have already been discussed; and
- alternative power sources, such as sails, solar cells, etc.

7.31 Additional to these technologies, regulatory developments to improve other aspects of shipping may have impacts on the energy efficiency of ships. Such regulatory developments include topics like anti-fouling, air emission reductions, ballast water requirements, regulation of speed (to reduce whale strikes), requirements for double hulls, new construction standards, and requirements for ice strengthening of hulls. These factors were discussed and their impacts were considered when determining scenario values for technological improvements. The parameters related to improvement of transport efficiency are shown in Table 7.12. These values are applied to the fleet average. Since only a limited portion of the fleet will be changed by 2020, the technology-driven part of the improvement in efficiency is assumed to be modest.

Aggregate improvements in transport efficiency

7.32 Assumptions of aggregate improvements in transport efficiency are shown in Table 7.13. These values are derived from the above discussion, acknowledging that different pathways could lead to similar reductions. The aggregate values for 2050 also account for structural changes to the fleet that could occur in the period beyond 2020. Historic average efficiencies of newbuild vessels are calculated in paragraphs 9.13 to 9.15. In order to put the inputs into the scenarios into perspective, aggregate baseline improvements in efficiency are plotted with indicated historic efficiencies from paragraphs 9.13 to 9.15, as shown in Figure 7.4. The data for historic efficiency end in 1995. The gap between 1997 and 2007 has been covered in the figure by linear interpolation at the same rate as estimated for the period 2007–2050.

Developments in marine fuels

7.33 The amount of CO_2 emitted from ships depends on the type of fuel. For instance, certain fuels may contain more carbon per energy output than other fuels, and hence may produce more CO_2 emissions per unit of work done. To capture this effect, future scenarios must contain assumptions of future fuel use. The choice of future fuels will depend on a number of factors, such as availability, price, practical

Table 7.13 *Inputs to the scenarios: aggregate improvements in efficiency (fleet average values) compared to efficiencies in 2007 as the base year*

	All scenario families		
	Base	**High**	**Low**
2050			
Ocean-going shipping	–39%	–58%	–5%
Coastwise shipping	–39%	–65%	–5%
Container	–39%	–75%	–5%
2020			
Ocean-going shipping	–12%	–22%	0%
Coastwise shipping	–12%	–22%	0%
Container	–12%	–39%	0%

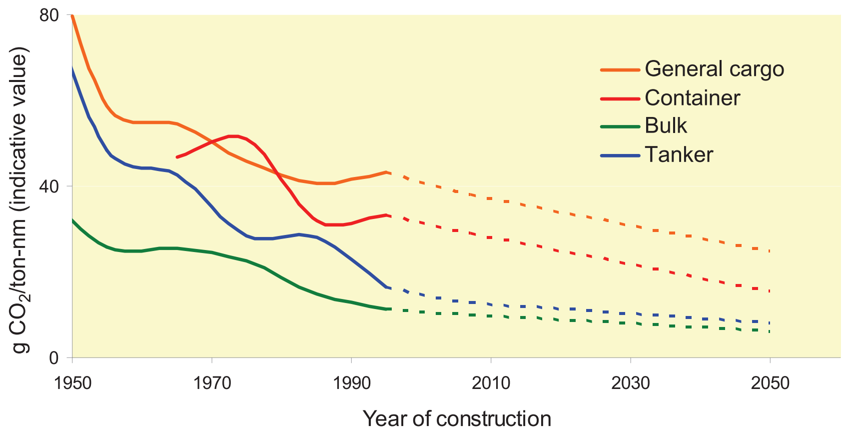


Figure 7.4 *Baseline improvements in efficiency and indicated historic improvements*

suitability for use on board ships, and regulations. With respect to fuel, regulations that need to be considered are those in the revised MARPOL Annex VI.

7.34 The SRES scenarios contain predictions of world energy use, categorized by primary energy source. Primary energy is the source of all energy on earth and, therefore, the ultimate source of all useful work. At an aggregate level, these sources are:

- coal;
- oil;
- gas;
- nuclear (labelled "non-fossil electric" for scenario B1);
- biomass; and
- other renewable sources.

Naturally, global energy trends will be reflected in shipping to a certain extent; however, a move away from traditional oil fuels would require a significant pull. In these scenarios, the pull would be economic, since there is no regulatory development in these scenarios to demand switching of fuels. A brief discussion on the suitability of the above fuels for use on board ships follows.

Coal

7.35 Technically, coal propulsion could be realized with a boiler/steam turbine arrangement. This is not considered attractive, due to aspects such as the need to remove sulphur oxide (SO_x) emissions, the low thermal efficiency, requirements to heat the boiler when the vessel is in port and the need for disposal of the combusted coal residuals and ash. It is also possible to manufacture liquid fuels from coal, which would be very suitable for use on board ships. Such synthetic fuels would be virtually sulphur-free [13]. There is currently a strong interest in coal-to-liquid technology, and such plants are being planned in the USA and in China [14]. These synthetic hydrocarbon fuels would have a carbon fraction different from coal but similar to diesel fuels; however, emissions of CO_2 related to their production are higher than those of petroleum fuels [25]. It has been reported that, even if carbon capture and storage was applied to capture 90% of the CO_2 emissions from a coal-to-liquid conversion plant, the net carbon emissions from coal-to-liquid fuel would be higher than for conventional road fuel [14].

Oil

7.36 Oil is currently the only significant energy source for international shipping. A significant driving force would be needed to change this; hence oil-derived fuels are considered the default choice in all scenarios. Taking the revised MARPOL Annex VI into account, oil-derived marine fuels can be classified as "global distillates" and "ECA distillates". The principal difference between these fuels is the difference in sulphur limits. The carbon content of these fuels would not be very different when measured on an energy basis.

Gas

7.37 Natural gas, when stored in a liquid state as liquefied natural gas (LNG), is predicted by many as a coming fuel for ships. Key drivers for this expected development are low emissions of nitrogen oxides (NO_x), SO_x and particulate matter (PM) from LNG-fuelled ships and the attractive price of LNG compared to distillate fuels. The most important technical challenge is finding the necessary space for storage of the fuel on board the ship and the availability of LNG in the bunkering ports. Therefore, LNG is primarily interesting in a context of coastwise shipping, where the range of the ship is less of an issue and the next port of bunkering is more predictable. LNG could also become an interesting fuel for tankers, since there is considerable space available for LNG fuel tanks on deck. LNG ships would be particularly attractive in NO_x emission control areas since they can meet Tier III emission levels without after-treatment. Natural gas can also be processed to create Fischer–Tropsch diesel (FTD) for use in diesel engines. However, in this case, the NO_x benefit associated with LNG operation would be lost.

7.38 LNG contains more hydrogen and less carbon than diesel fuels; hence emissions of CO_2 are reduced. Unfortunately, increased emissions of methane (CH_4) reduce the net effect to about 15% reduction of CO_2 equivalents [15]. The cost of bulk LNG is about the same as that of residual fuel oil, and it is significantly cheaper than distillate fuels.

Nuclear

7.39 Installing nuclear reactors on board is not foreseen to be an interesting option for international shipping, for environmental, political, security and commercial reasons. The use of electric power derived from nuclear plants or other non-fossil electricity sources for propulsion (as opposed to use while at berth) is not considered feasible due to the low power density, cost, weight and the size of batteries.

Biomass

7.40 These fuels include current "first-generation" biofuels made from sugar, starch, vegetable oil, or animal fats, using conventional technology. Amongst these, biodiesel (i.e. Fatty Acid Methyl Esters, FAME) and vegetable oils can readily be used for ship diesels. In rough terms, biodiesel could be substituted for distillate fuels and vegetable oils could be substituted for residual fuels. With present (first-generation) biofuels, there will be certain issues (such as stability during storage, acidity, lack of water-shedding, plugging of filters, formation of waxes and more) which suggest that care must be exercised in selecting the fuel and adapting the engine [16, 17, 18, 19]. Blending bio-derived fuel fractions into diesel or heavy fuel oil is also feasible from a technical perspective; however, compatibility must be checked, as is also the case with bunker fuels. Future biomass-to-liquid fuels manufacturing processes can be designed to synthesize various fuels that are suitable for use on board ships. Currently, biofuels are significantly more expensive than oil-derived fuels [16]. This would have to change if there is to be an incentive to use such fuels on board ships in these non-regulated scenarios.

Other renewable sources

7.41 Other renewable energy sources for ships include the renewable energy that can be generated on board (principally wind, solar-generated and ship-motion-generated energy) and renewable energy generated on shore and transferred to the ship by way of an energy carrier such as hydrogen. Within the structure of the scenario model, the generation of renewable power on board the ship would be modelled as energy savings and would not affect the carbon content of the fuel, while the use of renewable energy from land would be considered a fuel and the carbon content of the fuel would be affected accordingly. The use of renewable energy from land would have to be more cost-effective than alternative fuels (such as oil-derived) if they are to be used in these non-regulated scenarios.

Penetration of new fuels into the maritime transport industry

7.42 For this analysis, we considered the potential market penetration for each family of scenarios, based on seven potential fuels: (1) marine distillates; (2) heavy fuel oil; (3) LNG; (4) LPG; (5) biodiesel; (6) synthetic diesel such as FTD; and (7) other renewable fuels. When considering market penetration for the various scenarios, it is noted that:

1. oil is a significant primary energy source in 2020 and 2050 in all scenarios (16–28% of world's primary energy in 2050);
2. in 2050, fossil fuels contribute from 57% to 82% of all primary energy in the SRES scenarios; and
3. previous estimates based on SRES scenarios [11] range the fuel consumption for shipping in 2050 from 400 to 810 million tonnes. This corresponds to 22–32 EJ or 10–15% of the global primary oil energy as specified for 2050 in the SRES scenarios.

7.43 Further, it is assumed that the sulphur regulations in the revised MARPOL Annex VI are adopted and that a global cap of 0.5% sulphur is applied in 2020, with the opening for alternative equivalent routes to compliance.

7.44 It is thus considered that the SRES scenarios permit the continued use of oil-based fuels, although the cost would be expected to be higher. Therefore, in these scenarios for regulation of non-GHG, the move from oil-derived fuels would have to be motivated by economy. Since there are already binding targets for reduction of GHG emissions on land, it is assumed that biofuels would fetch a better price there and would not be used by ships. The same situation would apply for the use of renewable energy from land.

7.45 It may be assumed that coal-to-liquid fuels could become economically attractive in scenarios A1FI and A2, where coal is a major source of energy. Some of this fuel could be directed to the market. Natural gas is an important energy source in all SRES scenarios. LNG propulsion would appear attractive for coastwise shipping in all scenarios. LNG could be particularly interesting on tank ships, where storage of fuel in tanks above deck is expected to be feasible with limited negative impacts. Based on the above, we established the general assumptions for market penetration shown in Table 7.14 and in Table 7.15.

Table 7.14 *Future fuel scenarios for 2020*

Fuel	A1B	A1FI	A1T	A2	B1	B2
LNG	5% of coastwise	5% of coastwise	10% of coastwise + 5% of tank ships†	5% of coastwise	10% of coastwise + 5% of tank ships†	10% of coastwise + 5% of tank ships†
Synthetic diesel*	None	None	None	None	None	None
Distillates	Balance	Balance	Balance	Balance	Balance	Balance

* Based on coal or other competitive feedstock.
† Ocean-going crude oil tankers, all size categories.

Table 7.15 *Future fuel scenarios for 2050*

Fuel	A1B	A1FI	A1T	A2	B1	B2
LNG	25% of coastwise +10% of tank ships†	25% of coastwise + 10% of tank ships†	50% of coastwise + 20% of tank ships†	25% of coastwise + 10% of tank ships†	50% of coastwise + 20% of tank ships†	50% of coastwise + 20% of tank ships†
Synthetic diesel*	None	20% of all ships	None	20% of all ships	None	None
Distillates	Balance	Balance	Balance	Balance	Balance	Balance

* Based on coal or other competitive feedstock.
† Ocean-going crude oil tankers, all size categories.

7.46 Carbon fractions (g of carbon/MJ) for each fuel type were calculated, based on assumptions regarding future fuel characteristics, such as impurities, molecular formula of hydrocarbons, energy content, and physical density, as shown in Table 7.16. These carbon fractions, categorized by the type of fuel, were applied to the values of market penetration that were used in the scenario to determine a weighted average carbon fraction for each category of vessel.

Table 7.16 *Fuel-specific carbon fractions used in scenario models*

Fuel	Carbon fraction (g of C/MJ)	Emission factor (kg of CO_2 /kg of fuel)
LNG	15.4	2.75
Synthetic diesel	19.7*	3.13*
Distillates	20.2†	3.19†

* Factors for synthetic diesel are based on typical data for Fischer–Tropsch diesel.
† A higher emission factor is estimated than the current inventory, due to the assumption that there will be less average impurities in future fuels.

CALCULATION OF EMISSIONS

7.47 The scenario model calculates energy consumption and emissions of CO_2 directly as a consequence of the key assumptions that have been presented in preceding sections.

7.48 Technology scenarios for exhaust gas pollutants other than CO_2 are not developed, but emissions are assumed to develop according to the regulations of MARPOL Annex VI. This implies that the specific emission rates of NO_x, SO_x and PM emissions will be reduced following the introduction of these regulations, while specific emission rates of other pollutants are assumed not to be reduced.

Future NO_x emissions

7.49 The revised Annex VI introduces a stepwise approach to reduction of emissions of NO_x. The original emission limit from Annex VI is now referred to as "Tier I", while future emission limits, named "Tier II" and "Tier III", will be introduced in 2011 and 2016. The updated regulation 13 of the revised MARPOL Annex VI is summarized in Table 7.17.

Table 7.17 *The NO_x limits in MARPOL Annex VI*

Tier	Date	NO_x limit (g/kW·h)		
		$n < 130$	$130 \leq n < 2000$	$n \geq 2000$
Tier I	2000	17.0	$45 \cdot n^{-0.2}$	9.8
Tier II	2011	14.4	$44 \cdot n^{-0.23}$	7.7
Tier III	2016*	3.4	$9 \cdot n^{-0.2}$	1.96

* Tier III applies only in emission control areas. "*n*" refers to rated engine speed (rpm).

7.50 Tier II emission factors are assumed to reduce proportionally with the emission regulation. For low-speed engines, the emission factor is assumed to be 14.4/17 (85%) of Tier I. For medium-speed engines, the emission factor is assumed to be 80% of Tier I. (Table 7.18). For Tier III, it is assumed that all engines are operated close to the emission limit. Emission from LNG-using engines is based on measurement data from MARINTEK and from manufacturers of engines.

Table 7.18 *Estimated NO_x emission factor by emission standard and engine type (kg/tonne of fuel)*

	Tier 0	Tier I	Tier II	Tier III
SSD*	90	78	66	18
MSD†	60	51	41	12
LNG‡	6	6	6	6

* SSD: slow-speed diesel engines.
† MSD: medium-speed diesel engines.
‡ LNG: all engines using LNG as fuel.

7.51 Fleet average emission factors depend on the composition of the fleet each year, which depends on vessel lifetimes and the growth of the fleet. Growth of the fleet is also linked with reductions in speed; therefore speed reductions could have an indirect positive effect on NO_x by accelerating the introduction of new ships and engines. Future emission factors for NO_x, based on a scenario of growth of the fleet by 3% per year and average ship lifetime of 30 years, are shown in Figure 7.5. This figure shows emission factors for SSD and MSD engines within and outside ECAs for future years.

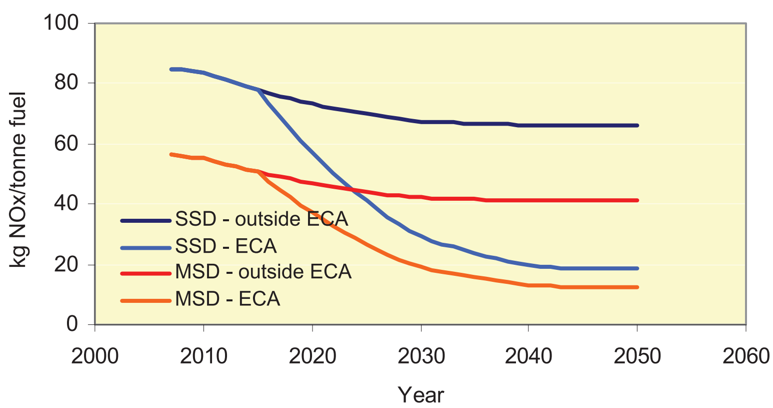


Figure 7.5 *Future NO_x emission factors (3% fleet growth per year, 30 year vessel life)*

Future SO_x emissions

7.52 New fuel sulphur emission limits are given in the revised MARPOL Annex VI. Present-day data for sulphur content of fuels are available from the IMO sulphur monitoring programme [26]. Future IMO limits on the sulphur content of fuel are shown in Table 7.19. Scenarios for reductions in sulphur emissions

Table 7.19 *Fuel sulphur limits in MARPOL Annex VI*

	Global	ECA
Present	4.50%	1.50%
1 July 2010		1.00%
1 January 2012	3.50%	
1 January 2015		0.10%
1 January 2020*	0.50%	

* This may be postponed to 2025, subject to review in 2018.

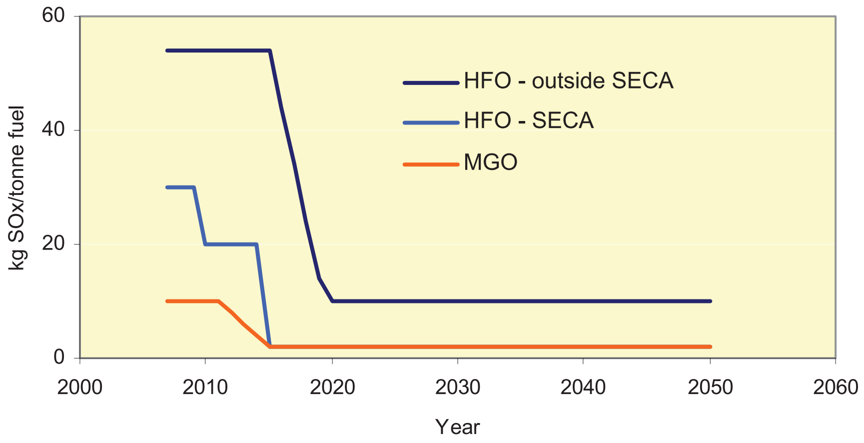


Figure 7.6 *Future SO_x emission factors used in scenarios. The future limit of 3.50% in 2012 on global sulphur content is not expected to influence the average emission factor*

as a consequence of these regulations are illustrated in Figure 7.6. Note that the 3.50% global limit introduced in 2012 is not expected to affect the average emission factor since the global average is presently 2.70%.

Future emissions of particulate matter

7.53 Particulate matter (PM) is a mix of non-volatile and semi-volatile compounds that do not fully participate in combustion or that are produced during combustion processes at high temperatures and pressures. For ships, PM often includes ash and other non-combustible residual contaminants, sulphur-related compounds that form aerosols (such as sulphate), condensed water particles, complex organic compounds that are referred to generally as "organic material", and small unburned carbon particles that are referred to as "elemental carbon" (also known as "soot" when they are visible in size or by their large number). Emissions of particulate matter depend partly on amounts of sulphur in fuel, especially the complex organic material that is associated with designs of cylinder lubricant that are matched to the sulphur content of the fuel and that discharge with other exhaust mass-flow. Ash and other residual contaminants are also typically found in proportion to the amount of sulphur in the fuel, although not directly dependent. Reduction in fuel-derived sulphur emissions will thus also reduce the emissions of particulate matter. The relationship between emission of PM and fuel composition, measured in a two-stroke laboratory engine that was provided by Germanischer Lloyd, is shown in Figure 7.7.

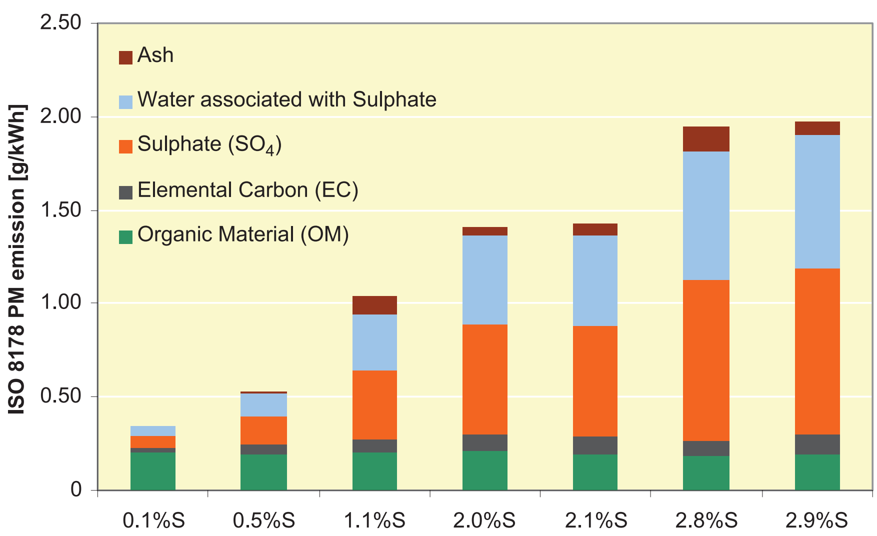


Figure 7.7 *The compositions of particulate matter obtained from different fuel types, Germanischer Lloyd [24]*

These data illustrate that:

1. PM ash is significantly reduced in a step when the sulphur content of fuel is < 1% (distillate);
2. Sulphate and associated water is correlated to the amount of sulphur in a fuel;
3. Elemental carbon is correlated to the amount of sulphur in a fuel; and
4. Organic material is not affected by the amount of sulphur in a fuel.

7.54 Using the data provided by Germanischer Lloyd, and maintaining the overall emission factor for PM in the CORINAIR Emissions Guidebook, the following future PM emissions are generated. As indicated in Figure 7.7 and Table 7.20, the composition of the PM at 0.1% sulphur is very different from that at 2.7% sulphur. Therefore, although significant reductions in amounts of PM are predicted, the compositions of future PM might be different from those of present PM.

Table 7.20 *Scenarios for emissions (kg/tonne of fuel) of present and future PMs*

	2.7% S	**0.5% S**	**0.1% S**
Organic material (OM)	0.67	0.66	0.68
Elemental carbon (EC)	0.34	0.17	0.08
Sulphate (SO_4)	3.02	0.52	0.22
Water associated with sulphate	2.42	0.42	0.17
Ash	0.25	0.03	0.00
Total	6.70	1.79	1.16

Emission factor summary

7.55 Assuming that fuel consumption within SECAs stays at 8% of global fuel (indicative of present levels), a fleet growth of 3% annually and an average vessel lifetime of 30 years, it is possible to derive composite emission factors for emission scenarios. The emission factors differ between the storylines, due to changes in fuel assumptions. Technology scenarios for the different IPCC storylines have not been developed.

Table 7.21 *Emission factors (kg/tonne fuel equivalent) in 2020 for all scenarios*

	A1B	**A1F**	**A1T**	**A2**	**B1**	**B2**
NO_x	61.0	61.0	59.8	61.0	59.8	59.8
SO^*_x	9.2	9.2	9.0	9.2	9.0	9.0
PM*	1.7	1.7	1.7	1.7	1.7	1.7
CO	7.4	7.4	7.4	7.4	7.4	7.4
NMVOC	2.4	2.4	2.4	2.4	2.4	2.4
CH_4	0.3	0.3	0.3	0.3	0.3	0.3
N_2O	0.1	0.1	0.1	0.1	0.1	0.1

* Full reductions, as per current Annex VI, are assumed to be in effect by 2020. Fuel consumption within ECA is 8%.

Table 7.22 *Emission factors (kg/tonne fuel equivalent) in 2050 for all scenarios*

	A1B	**A1F**	**A1T**	**A2**	**B1**	**B2**
NO_x	49.1	49.1	45.0	49.1	45.0	45.0
SO^*_x	8.6	6.7	7.8	6.7	7.8	7.8
PM*	1.6	1.6	1.4	1.6	1.4	1.4
CO	7.4	7.4	7.4	7.4	7.4	7.4
NMVOC	2.4	2.4	2.4	2.4	2.4	2.4
CH_4	0.3	0.3	0.3	0.3	0.3	0.3
N_2O	0.1	0.1	0.1	0.1	0.1	0.1

* Full reductions, as per current Annex VI, are assumed to be in effect by 2020. Fuel consumption within ECA is 8%.

RESULTS

7.56 The scenario analysis involved creating specific scenarios in each of the six families of scenario described above. For CO_2, we looked at all possible combinations of growth in demand (base, low, high), efficiency of transport (base, low, high), and impacts of reduction in speed (base, low, high). This approach gave us a total of $3 \times 3 \times 3 = 27$ scenarios for each family of scenarios, or a total of $6 \times 27 = 162$ scenarios for CO_2 for each year (2020 and 2050). We used the vessel-based carbon fraction identified for each family of scenarios as described above. For other emissions, we calculated future emissions based on baseline assumptions.

7.57 Trajectories of emissions of CO_2 for base scenario values as well as the maximum and minimum values observed within these 162 scenarios are shown in Figure 7.8. The results are also presented in Table 7.23 and Table 7.24. Other emissions are shown in Figure 7.9, Table 7.25 and Table 7.26. For international shipping, the base scenarios indicate CO_2 emission growth in the range of 220%–310% for the period 2007–2050. For total shipping, CO_2 emission growth is estimated to about 230%–350% in the same period.

7.58 Aside from the Min and Max scenarios, the scenarios in Figure 7.8 are characterized by their similarities. This is a result of the broadly similar technology pathway that has been suggested for ships in these scenarios in spite of different storylines and different compositions of primary energy sources. The difference between the scenarios is driven principally by differences in demand and the type of fossil fuel that is used. In these scenarios, increased use of non-emitting energy which may have impact on a global scale, such as nuclear and biomass, does not penetrate significantly into the shipping sector.

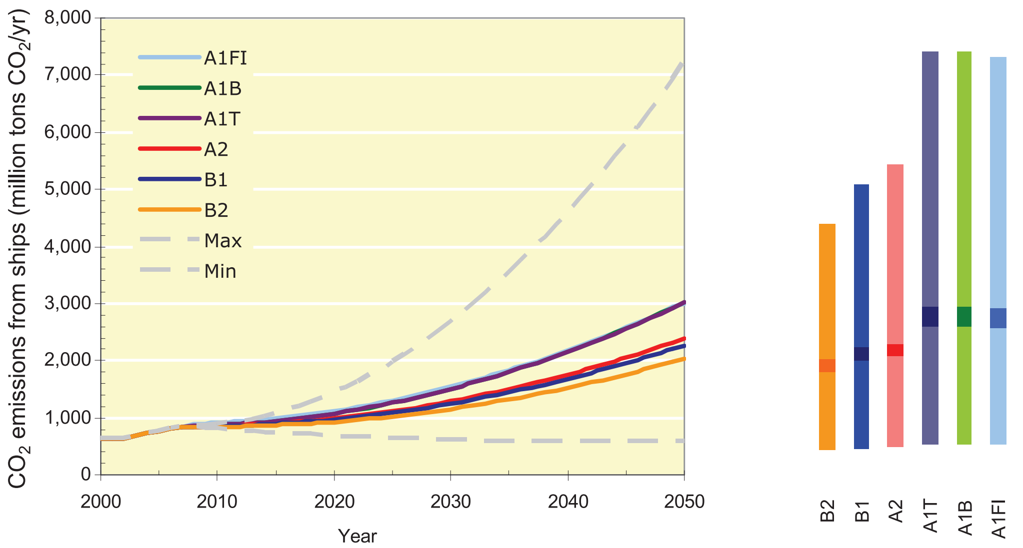


Figure 7.8 *Trajectories of the emissions from international shipping. Columns on the right-hand side indicate the range of results for the scenarios within individual scenario families*

Table 7.23 *Emissions of CO_2 (million tonnes/year) from international shipping*

	2020			2050		
	Base	**High**	**Low**	**Base**	**High**	**Low**
A1FI	1,058	1,440	770	2,648	7,228	692
A1B	1,057	1,447	770	2,681	7,344	693
A1T	1,058	1,447	770	2,668	7,341	688
A2	982	1,275	740	2,194	5,426	637
B1	959	1,252	734	2,104	5,081	616
B2	925	1,160	719	1,903	4,407	588

Table 7.24 *Projected annual growth in emissions of CO_2 from shipping, 2007–2050**

	Base	High	Low
A1FI	2.7%	5.1%	–0.4%
A1B	2.7%	5.2%	–0.4%
A1T	2.7%	5.2%	–0.4%
A2	2.2%	4.4%	–0.6%
B1	2.1%	4.3%	–0.7%
B2	1.9%	3.9%	–0.8%

* The same rate of growth is assumed to apply to domestic and international shipping.

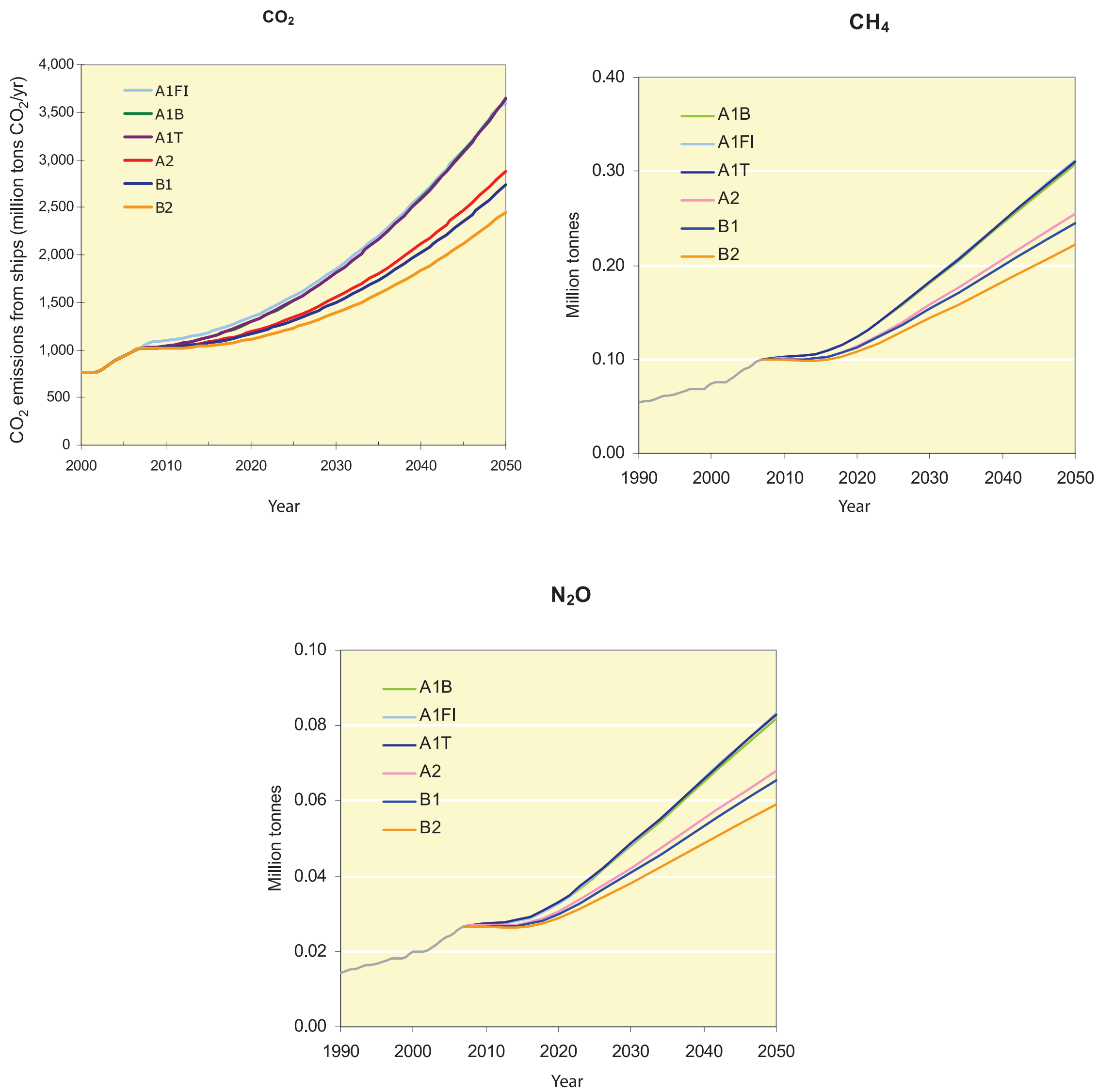


Figure 7.9 *Emission scenario trajectories for GHG emissions – total shipping (exhaust emissions only)*

DISCUSSION

7.59 The scenarios that have been developed show significant increases in activity and emissions from ships. This is also the result of previous research on future ship emissions, including the 2000 IMO Study on greenhouse gas emissions from ships. The predicted future emissions of CO_2 in this study are higher

Table 7.25 *Scenarios for emissions (million tonnes/year) from total shipping in 2020*

	A1B	A1F	A1T	A2	B1	B2
NO_2	25.1	25.1	24.6	23.3	22.3	21.5
SO_2	3.8	3.8	3.7	3.5	3.4	3.2
PM	0.7	0.7	0.7	0.7	0.6	0.6
CO	3.0	3.0	3.0	2.8	2.8	2.7
NMVOC	1.0	1.0	1.0	0.9	0.9	0.9
CO_2	1,294	1,293	1,294	1,188	1,167	1,114
CH_4	0.12	0.12	0.12	0.11	0.11	0.11
N_2O	0.03	0.03	0.03	0.03	0.03	0.03

Table 7.26 *Scenarios for emissions (million tonnes/year) from total shipping in 2050*

	A1B	A1F	A1T	A2	B1	B2
NO_2	50.3	51.0	46.7	41.6	36.8	33.3
SO_2	8.8	6.9	8.0	5.7	6.3	5.7
PM	1.6	1.7	1.5	1.3	1.2	1.1
CO	7.6	7.7	7.7	6.3	6.0	5.5
NMVOC	2.5	2.5	2.5	2.0	2.0	1.8
CO_2	3,595	3,644	3,634	2,878	2,735	2,449
CH_4	0.31	0.31	0.31	0.25	0.25	0.22
N_2O	0.08	0.08	0.08	0.07	0.07	0.06

than previous estimates published by Eyring *et al.* in 2005 [11] but in the same range as recently developed shipping scenarios, up to 2050, from the EU project QUANTIFY (OECD, 2008 [23]).

7.60 The effect of present and future IMO regulations on emissions of NO_x and SO_x/PM is apparent in Figure 7.10. Emissions of NO_x are stabilized and even reduced towards 2020, whereafter they eventually increase. The estimate is based on the present number of emission control areas. Introduction of more ECAs will result in larger reductions. This is also the case for SO_x and PM, where reductions are already substantial. Since the chemical composition and the distribution of particle sizes of PMs change with the reductions in sulphur content of fuels, the environmental and public health benefit achieved need not be proportional to the reduction in PM emissions that is shown.

7.61 There are a number of important observations that can be made from our analysis of the results of scenarios. One of the key insights is that the demand for transport is the most important variable affecting the growth in future emissions of CO_2. Having said this, there are scenarios that show reductions in emissions. These scenarios have estimates of very low growth and high transport efficiency. Reduced growth in seaborne transport does not necessitate reduced growth in the world-wide economy. Increased recycling, more regional trade and a more service-oriented economy could contribute to the decoupling of economic growth from seaborne trade.

7.62 Another insight is based on the comparison of the A1 families of scenarios, all of which cluster around common values of emissions. The differences in the A1 families are mostly driven by assumptions in changing energy patterns globally. In the IPCC SRES scenarios, the differences between a "balanced", a "fossil-intensive", and a "technologically advanced" future are more significant, due to the role that alternative low-carbon fuels have in non-shipping sectors, such as the production of electricity, light-duty vehicles, and industrial processes. However, with international shipping, the movement of global energy markets from high-carbon to low-carbon fuels may have a less significant impact. This is because the transition to low-carbon fuels in a sector as large as the shipping industry is likely to take decades. Also, we expect that this transition will be realized in other sectors before it occurs in marine shipping.

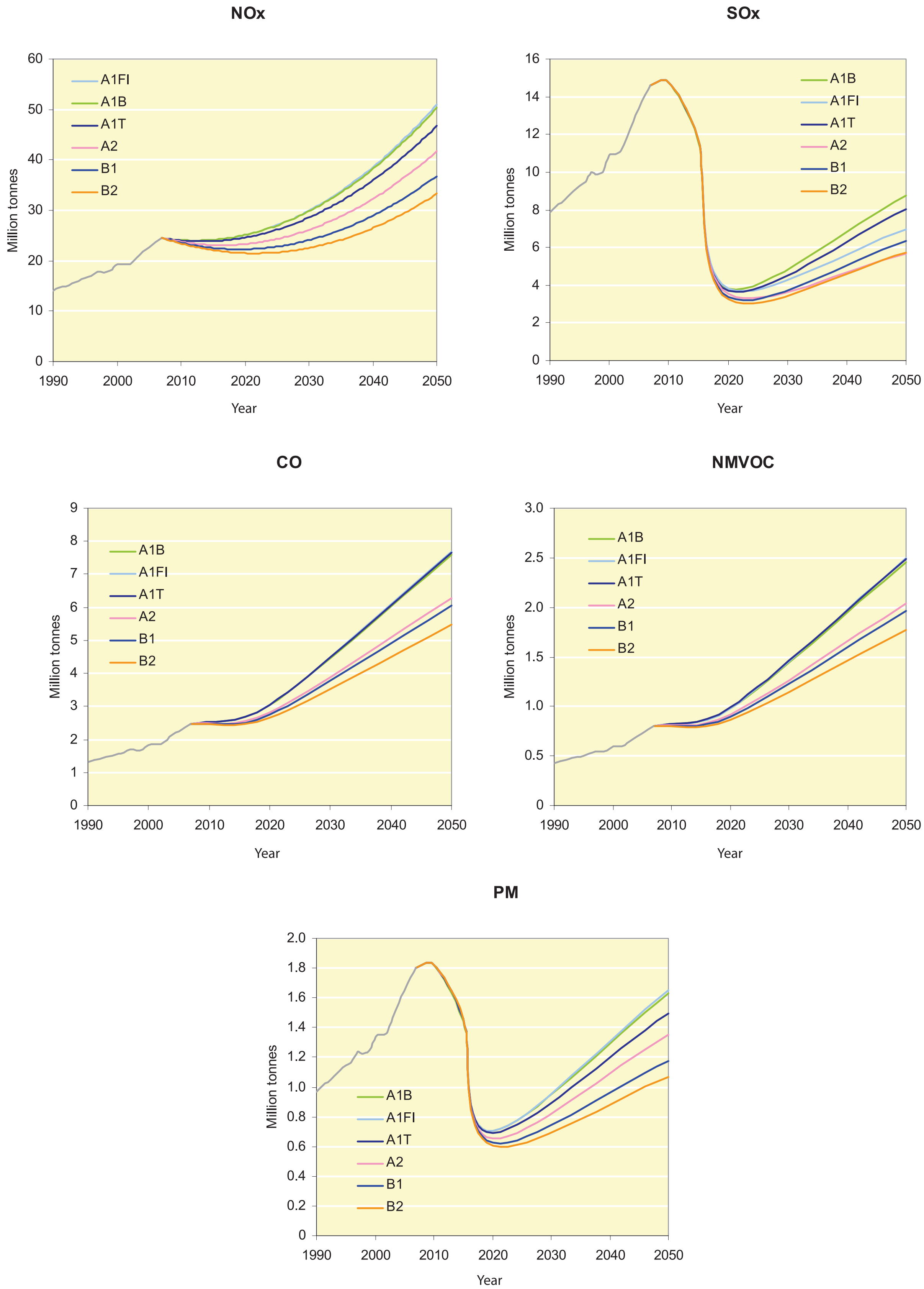


Figure 7.10 *Emission scenario trajectories for other relevant substances – total shipping (exhaust emissions only)*

CONCLUSIONS

7.63 Reductions in emissions beyond what is shown in the minimum scenarios would require radical changes compared to the assumptions in our model. Examples of such changes include:

1. abrupt decoupling between seaborne trade and global economic growth – in our model, the growth in demand for transport is already lower than the correlation with GDP suggests; hence such decoupling must be rapid and very significant;
2. rates of global economic growth that are significantly lower than the B2 scenario;
3. extreme shortages of fossil energy compared to the SRES scenarios – according to SRES scenarios, by 2050 the total consumption of primary energy ranges from 160% to 284% of the values in 2010 and fossil fuels cover from 57% to 82% of global demand for primary energy; and
4. introduction of unexpected technologies.

Therefore, the scenarios do not eliminate the possibility of reductions in emissions of CO_2. However, they do signal a need for fundamental change in order to achieve such reductions.

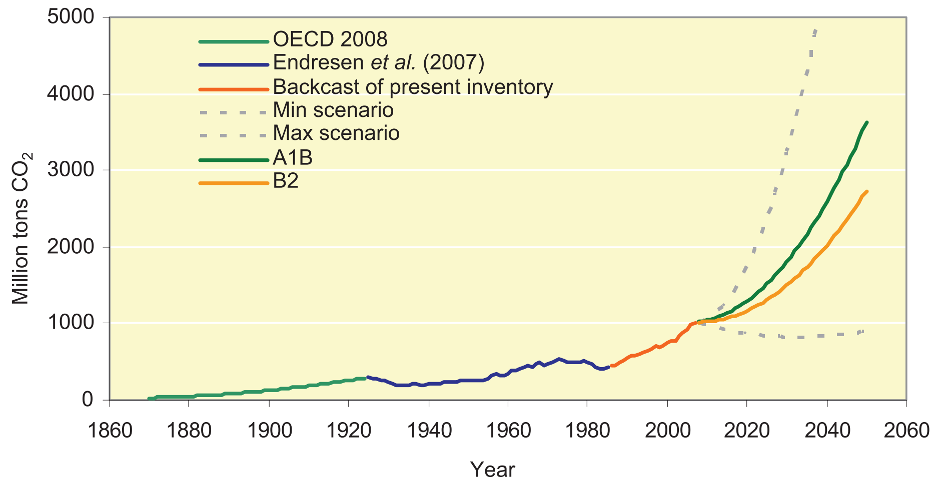


Figure 7.11 *Scenarios for emissions of CO_2 from ships in a historic perspective*

7.64 On the whole, maritime shipping shows significant advantages in carbon emissions when compared to road and air freight, and is competitive on this front with respect to rail, as will be seen in Chapter 9. Thus, although international shipping may show increases in emissions, due to increasing demand between now and 2050, these increases may be designed to offset what would be higher emissions from other modes of transport (i.e. road and air). Shifting the mode from truck to ship, for example, may increase emissions from ships, but will have an overall beneficial impact on the emissions from the system for movement of goods as a whole.

REFERENCES

1 Chermack, T.J., Lynham, S.A. and Ruona, W.E.A. 2001. "A review of scenario planning literature". *Futures Research Quarterly*, 17(2): 7–31.

2 Porter, M.E. 1980. *Competitive Strategy: Techniques for Analyzing Industries and Competitors*. Free Press, New York.

3 Schwartz, P. 1991. *The Art of the Long View*. Doubleday Currency, London.

4 Shoemaker, P.J.H. 1995. "Scenario planning: a tool for strategic thinking." *Sloan Management Review*, 37(2): 25–40.

5 Winebrake, J.J. 2003. "The future impacts of electric drive vehicles: A case of normative scenario modelling". *Futures Research Quarterly*, 19(1): 5–25.

6 Nakicenovic, N., Alcamo, J., Davis, G. and Vries, B.D. 2000. *Special Report on Emissions Scenarios*. Cambridge University Press: Cambridge, UK.

7 Nakicenovic, N. and Swart, R. (editors). 2007. *Special Report on Emissions Scenarios: A Special Report of Working Group III of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, UK. http://www.grida.no/publications/other/ipcc%5Fsr/?src=/climate/ipcc/emission/index.htm

8 SEDAC. The SRES Emissions Scenarios. http://sedac.ciesin.columbia.edu/ddc/sres/index.html (28 February 2008).

9 Schwartz, P. 1991. *The Art of the Long View: Planning for the Future in an Uncertain World*. Currency Doubleday, New York, USA, p. 272.
10 Review of Maritime Transport, United Nations Conference on Trade and Development (UNCTAD) 2007.
11 Eyring, V., Köhler, H.W., Lauer, A. and Lemper, B. 2005, "Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050". *J. Geophys. Res*. 110, D17306, doi:10.1029/2004JD005620.
12 BLG 12/INF.10 Input from the four subgroups and individual experts to the final report of the Informal Cross Government/Industry Scientific Group of Experts.
13 Davies, G.O. and Freese, R.G. 1981. "The preparation and performance of coal derived diesel fuel". Proceedings of the 14th International Congress on Combustion Engines, Diesel Engines, Helsinki, Finland, 1981.
14 Vallentin, D. 2008. "Driving forces and barriers in the development and implementation of coal-to-liquids (CtL) technologies in Germany". *Energy Policy*, 36(6): 2030–2043.
15 Einang, P.M. 2007. "Gas fuelled ships". Proceedings of the 25th CIMAC World Congress on Combustion Engine Technology, Vienna, Austria, 21–24 May 2007, Paper 261.
16 Opdal, O.A. and Fjell Hojem, J. 2007. "Biofuels in ships: A project report and feasibility study into the use of biofuels in the Norwegian domestic fleet". ZERO report, 18 December 2007.
17 Ollus, R. and Juoperi, K. 2007. "Alternative fuels experiences for medium-speed diesel engines". Proceedings of the 25th CIMAC World Congress on Combustion Engine Technology, Vienna, Austria, 21–24 May 2007. Paper 234.
18 Matsuzaki, S. 2004. "The application of the waste oil as a bio-fuel in a high-speed diesel engine". Proceedings of the 24th CIMAC World Congress on Combustion Engine Technology, Kyoto, Japan, 7–11 June 2004.
19 Ohgawara, T., Okada, H., Tsukamoto, T., Iwasawa, K. and Ohe, K. 2007. "Application study of waste-vegetable oils as a bio-fuel for diesel engine by high-density cavitation". Proceedings of the 25th CIMAC World Congress on Combustion Engine Technology, Vienna, Austria, 21–24 May 2007. Paper 196.
20 Dahle, Ø. 2008. The Climate Challenge. 29th International Bunker Conference, 23–25 April 2008, Copenhagen, Denmark.
21 OPRF: "Research Study: The World's Changing Maritime Industry and a Vision for Japan". ISBN 978-4-88404-212-7. Note: A pdf file for this report is available in English at http://www.sof.or.jp/en/topics/08_04.php.
22 Brown, B.B. 1968. "Delphi Process: A methodology used for the elicitation of opinions of experts". Rand Corporation, Santa Monica, CA, USA. http://www.rand.org/pubs/papers/2006/P3925.pdf
23 OECD. 2008. Endresen, Ø. and Dalsøren, S. (main authors) "The environmental impacts of increased international maritime shipping – Past trends and future perspectives". Work produced by Det Norske Veritas and University of Oslo, Rep. no. ENV/EPOC/WPNEP/T(2008)5 7.
24 Kurok, C., Pawils, V., Brumm, H. and Götze, H.J. (Germanischer Lloyd). "Emission of particulate matter from marine diesel engines". Presentation at IMO BLG-WGAP 2, Berlin, 2007.
25 van Vliet, O.P.R., Faaij, A.P.C., *et al.* 2009. "Fischer–Tropsch diesel production in a well-to-wheel perspective: A carbon, energy flow and cost analysis". *Energy Conversion and Management*, 50(4): 855–876.
26 Sulphur Monitoring for 2008. IMO Secretariat, document MEPC 59/4/1.

8

Climate impact

INTRODUCTION

8.1 In recent years, questions have been raised regarding the nature and magnitude of the impact of the shipping sector on climate. Shipping emissions have been recognized as a growing problem for environmental policy makers (Corbett, 2003), as it has been realized that emissions from vessels have direct impacts on human health, contribute to regional acidification and eutrophication and also influence "radiative forcing" (RF)[1] of climate.

8.2 Developments in climate science research are regularly reviewed and assessed by the Intergovernmental Panel on Climate Change's (IPCC) Working Group I (WGI); the most recent report was published in 2007 (IPCC, 2007). IPCC (2007) did not specifically address shipping, and indeed only made brief mention of the effects of shipping, in the context of ship tracks, in chapter 2 of that report (Forster *et al.*, 2007). Thus, effects of shipping on climate have not been comprehensively assessed by the IPCC in the same way that, for example, aviation has (IPCC, 1999). The forthcoming assessment report of Eyring *et al.* (2009) is the most complete and up-to-date assessment of the effects of shipping on climate that is available in the scientific literature.

8.3 Shipping produces a wide range of emissions. Key compounds that are emitted are carbon dioxide (CO_2), nitrogen oxides (NO_x), carbon monoxide (CO), volatile organic compounds (VOC), sulphur dioxide (SO_2), black carbon (BC) and particulate organic matter (POM). Emissions of NO_x and other ozone precursors from shipping lead to formation of tropospheric ozone (O_3) and perturb the concentrations of hydroxyl radical (OH), and hence the lifetime of methane (CH_4).[2] The dominant component of the aerosol resulting from ship emissions is sulphate (SO_4), which is formed by the oxidation of SO_2; this arises from sulphur in the fuel.

8.4 Carbon dioxide is a direct greenhouse gas; emissions of NO_x, CO and VOCs are ozone precursors, which have been discussed in a number of studies (e.g., Lawrence and Crutzen, 1999; Kasibhatla *et al.*, 2000; Davis *et al.*, 2001; Endresen *et al.*, 2003; Eyring *et al.*, 2007a). In addition to the impact on tropospheric chemistry, particle emissions from shipping alter the physical properties of low clouds and have an impact on climate (Lauer *et al.*, 2007). Long, curved cloud structures arising from ship emissions can be observed from satellite images; these are commonly termed "ship tracks" (e.g., Durkee *et al.*, 2000; Schreier *et al.*, 2006; 2007). The emissions from shipping affect radiative forcing of climate (RF); this is the conventional climate metric, expressed in watts per square metre (W m^{-2}), that is used in climate science and by the IPCC, and is a change in the energy budget of the Earth's atmosphere relative to 1750 (a definition adopted by the IPCC, and used here also). RF is usually expressed as a global mean, and positive numbers imply warming while negative numbers imply cooling. The emissions and climate effects from shipping arise from:

- emissions of CO_2, which has a warming effect (positive RF);

1 A common metric to quantify impacts on climate from different sources is "radiative forcing" (RF), in units of W/m^2, since there is an approximately linear relationship between global mean radiative forcing and change in global mean surface temperature. RF refers to the change in the Earth – atmosphere energy balance since the pre-industrial period. If the atmosphere is subject to a positive RF from, for example, the addition of a greenhouse gas such as CO_2, the atmosphere attempts to re-establish a radiative equilibrium, resulting in a warming of the atmosphere.

2 Methane is a greenhouse gas, principally emitted by other sectors (agriculture, mining, etc.).

- emissions of NO_x, which result in the production of tropospheric O_3 (positive RF) and a reduction of ambient CH_4, a cooling effect (negative RF);
- emissions of sulphate particles (negative direct RF);
- emissions of soot particles (positive direct and indirect (snow) RF); and
- formation or change in low-level clouds (negative indirect RF).

8.5 The overall impacts of (any) emissions on climate are complex, and are summarized conceptually for the shipping sector in Figure 8.1. Emissions give rise to changes in the abundance of trace species in the atmosphere. Through atmospheric processes, these emission species may undergo atmospheric reactions, alter microphysical processes or be absorbed/removed by various sinks (land and water surfaces) through wet and dry deposition. These changes may then affect the radiative balance of the atmosphere through changes in the abundance of trace species, in atmospheric composition, and in the properties of clouds and aerosols. Such changes in RF may then affect climate in a variety of ways, e.g., global and local mean surface temperature, sea level, changes in precipitation, snow and ice cover, etc. In turn, these physical impacts have societal impacts through their effects on agriculture, forestry, energy production, human health, etc. Ultimately, all of these effects have a social cost, which can be very difficult to quantify. Clearly, as one steps through these impacts, they become more relevant but correspondingly more complex and uncertain in quantitative terms. In this study, we have evaluated climate impacts mostly based on changes in global mean RF and temperature response. It should be noted that this is a simplification, and even changes in local responses that are positive and negative and appear to cancel each other out (e.g., RF responses) may impact climate, in spite of a first-order indicator of such a metric as global mean RF having a small or zero response.

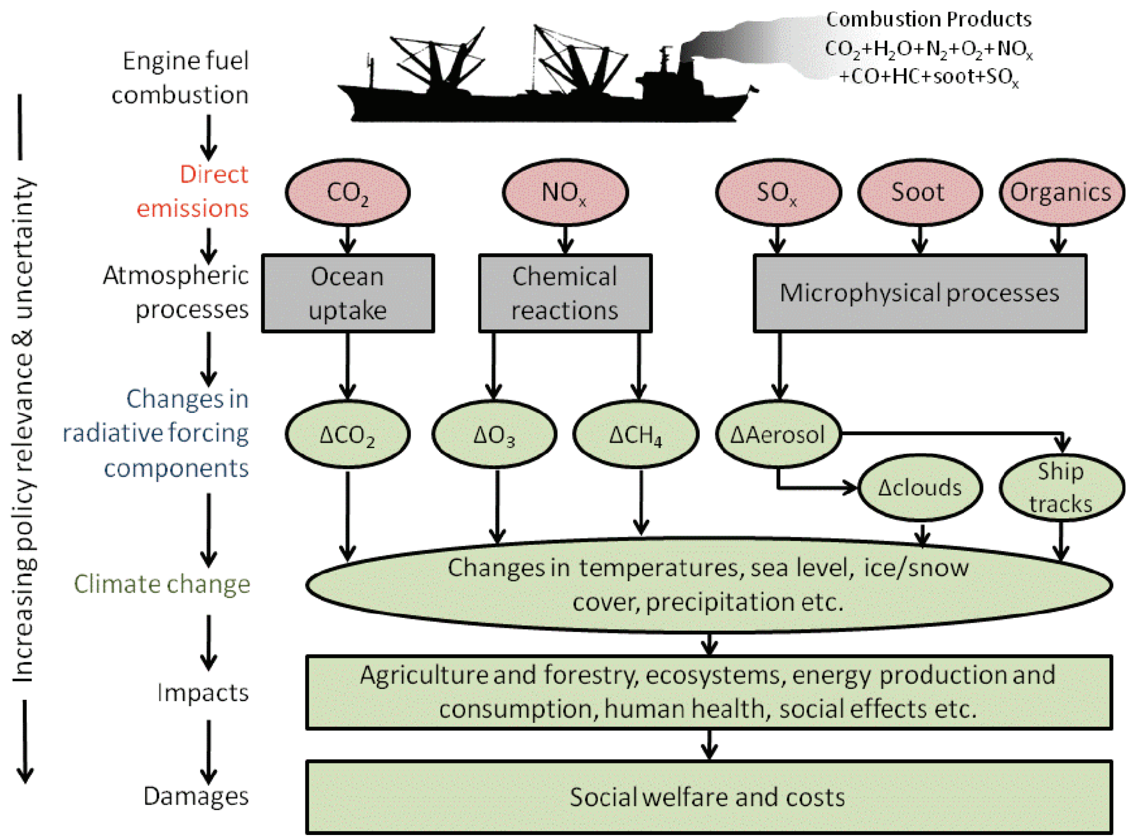


Figure 8.1 *Schematic diagram of the overall impacts of emissions from the shipping sector on climate change (from Lee et al., 2009a)*

8.6 The magnitude of present-day emissions from shipping has been discussed in other sections of this report. In the following sections we describe the methodology by which the RF and global mean temperature responses from shipping in 2007 were calculated; the resulting RF and temperature responses are given and compared with other values found in the literature. The potential role of shipping within a hypothetical climate-stabilization regime is also discussed, and overall conclusions over the response of the climate to effects arising from shipping are drawn in the final sub-section.

CALCULATION METHODOLOGY AND MODEL DESCRIPTION

8.7 In order to calculate the global mean RF and temperature responses from shipping emissions, a simplified carbon-cycle model was used to calculate the contribution of CO_2 emissions to marginal CO_2 concentrations and the resulting RF. The response of RF was then used in a linear climate-response model to calculate a global mean temperature response, which can be applied to any forcing agent.

8.8 For the non-CO_2 RF responses, a different approach was necessary, as these forcings are more complicated to calculate. The calculation of non-CO_2 responses from shipping emissions on atmospheric composition and cloudiness, for example, involves the use of more complex models (e.g., Lauer *et al.*, 2007; Eyring *et al.*, 2007a). The 2007 emissions that were determined in this study were used as input data to two such models; one was for tropospheric O_3 chemistry (MOZART v2; Horowitz *et al.*, 2003) and one for atmospheric composition that influences the abundance of aerosols and cloudiness (ECHAM5/MESSy1-MADE; Lauer *et al.*, 2007). In order to calculate the global mean time-evolved temperature response from non-CO_2 forcings, the RF for a given year was prescribed (from the results of more complex models), and a relationship to an annual emission rate was used as a proxy for calculating the year-by-year RF response. In this way, the resultant global mean temperature responses can then be calculated. The methodologies are described in more detail below.

Methodology to calculate time-evolved RF and temperature responses from shipping emissions

8.9 The climate-response model is a development of Sausen and Schumann (2000), previously applied to scenarios for emissions from aviation (Lee *et al.*, 2009b), which in turn is based upon the approach of Hasselmann *et al.* (1993; 1997). Some modifications and developments have been made to the model, which is now capable of addressing the full suite of shipping impacts (CO_2, NO_x impacts on O_3 and CH_4, direct and indirect effects from aerosols and their precursors; see Lim *et al.*, 2007 and Lee *et al.*, 2007).

8.10 The contribution of CO_2 emissions from shipping to ambient concentrations of CO_2 is assumed to be the difference between that from total "background" emissions and the calculated contribution from shipping as follows. The response of CO_2 concentrations, $C(t)$, to the rate of emission of CO_2, $E(t)$, was modelled following Hasselmann *et al.* (1997); this approximates to the results from the carbon-cycle model of Meier-Reimer and Hasselmann (1987), so that:

$$\Delta C(t) = \int_{t_0}^{t} G_C(t - t')E(t')\mathrm{d}t' \qquad (1)$$

and

$$G_C(t) = \sum_{j=0}^{5} a_j e^{-t/\tau_j} \qquad (2)$$

where τ_j is the e-folding time of mode j and the equilibrium response of mode j to a unit forcing is $a_j\tau_j$, using the mode parameters given in Table 8.1.

Table 8.1 *Coefficients of the impulse function G_C for CO_2 concentration (Schumann and Sausen, 2000)*

Mode j	**1**	**2**	**3**	**4**	**5**
a_j (ppbv/Tg (C))	0.067	0.1135	0.152	0.097	0.041
τ_j (year)	∞	313.8	79.8	18.8	1.7

8.11 The RF of CO_2 is dependent upon its own concentration because of spectral saturation, such that, in calculating the impacts of CO_2 from shipping, it is necessary to know the "background" RF (equation 3).

$$\Delta RF_{Shipping} = \Delta RF(C_{Background}) - \Delta RF(C_{Background} - C_{Shipping}) \quad (3)$$

8.12 Historical background CO_2 concentration data from 1800 until 1995, and thereafter SRES scenario data (IPCC, 2000) until 2100 (all natural and anthropogenic sources, including emissions from shipping), were used. The contribution of CO_2 from shipping was calculated explicitly, using equations (3) and (4), the concentration being assumed to be the difference between the background concentration and the concentration arising from shipping.

8.13 From the CO_2 concentrations, the RF was calculated. According to IPCC, the RF of CO_2 can be estimated from the logarithm of the concentration, which approximates the effect of saturation in RF with increased CO_2 concentrations.

8.14 Here, we use the expression from Ramaswamy *et al.* (2001), which utilizes an a coefficient of 5.35 from Myhre *et al.* (1998):

$$RF(t) = \alpha \lfloor \ln(C_{(t)} / C_{(0)}) \rfloor \quad (4)$$

The shipping emissions and the scenarios that were used in this work are described elsewhere in the report, including a description of the underlying assumptions. Figure 8.2 presents the historical and present-day emissions that were used. For emissions between 1870 and 1925, estimates from OECD (2008) were used. The CO_2 time series is continued with estimates from Endresen *et al.* (2007) between 1925 and 1985. The estimate of CO_2 emissions in 2007 from this study is 1050 Tg (CO_2)/year. Between 1986 and 2007 we used the backcast calculated from the evolution through time of freight tonne-miles (Fearnleys, 2007), with the point estimates from this study in 2007 taken as the reference year. This produced a smooth curve over the entire period from 1870 to 2007, as the backcast CO_2 of the present emissions inventory agrees well with the estimate for 1985 by Endresen *et al.* (2007).

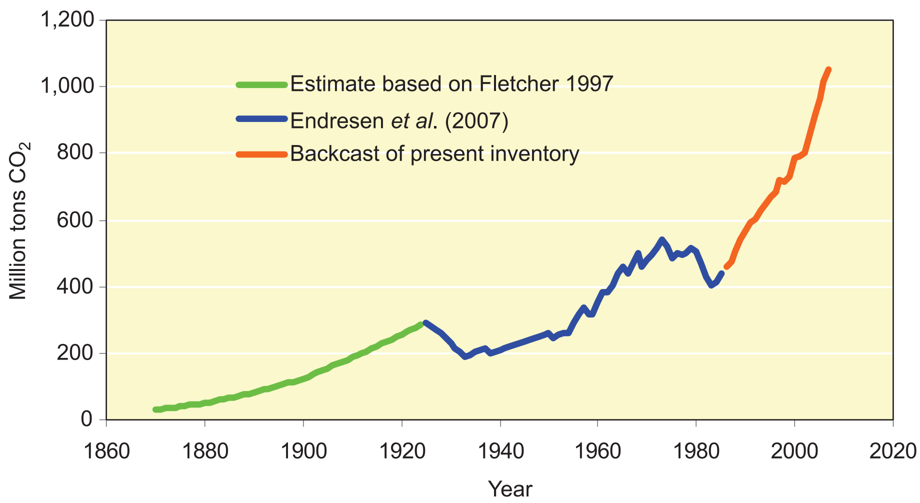


Figure 8.2 *Historical and present-day emissions of CO_2 from shipping*

8.15 The above methodology explicitly calculates the changes in CO_2 concentration and the resultant changes in RF. For non-CO_2 effects, an externally calculated RF for a particular effect is taken and related to a given emission rate, so that the change in RF over time can be calculated. It is necessary to have a complete history of RF in order to calculate the global mean temperature response. The externally calculated RFs for individual species and effects, the corresponding emission rates, the reference year and the source(s) that were used for temperature response calculations are given in Table 8.2.

8.16 It should be noted that the RF values given in Table 8.2 are referenced to a particular emission rate and year specified in the relevant source studies. Thus, for the same reference year, since the emissions that were determined in this present study are different, the above RFs will not be reproduced. It is assumed that the emission rates for various species in this report represent the best available estimates, and the RFs calculated therefore use these emissions for consistency.

8.17 The global mean temperature response for the various forcing agents was calculated by using the approach devised by Hasselmann *et al.* (1993), which has been widely used since (e.g., Hasselmann *et al.*, 1997; Sausen and Schumann, 2000; Shine *et al.*, 2005).

Table 8.2 *Input for the climate response model: non-CO_2 radiative forcings prescribed for shipping, relevant emission rate, reference year and source*

Forcing	Prescribed RF ($mW\ m^{-2}$)	Relevant emission rate (per year)	Reference year	Source
Ozone (from NO_x and other precursors of O_3)	26.0	5.43 (Tg of N)	2000	Eyring *et al.* (2009)
Methane reduction (from NO_x and other precursors of O_3)	−33.0	5.43 (Tg of N)	2000	Eyring *et al.* (2009)
SO_4 (direct)	−31.0	11.1 (Tg of SO_2)	2000	Eyring *et al.* (2009)
Black carbon (BC)	2.0	0.13 (Tg of BC)	2000	Eyring *et al.* (2009)
Particulate organic matter (POM)	−0.4	0.14 (Tg of POM)	2000	Eyring *et al.* (2009)
Indirect cloud	−66.0	8.3 (Tg of SO_2)	2000	Fuglestvedt *et al.* (2008)

8.18 The climate-response-function approach can be represented by a convolution integral, the use of which assumes that small perturbations to a system (here, climate) can be represented in a linearly additive manner. Thus, the response of a climate variable Φ at time (t) to a forcing $F(t)$ is:

$$\Phi(t) = \int_{t_0}^{t} G_\Phi\,(t - t')F(t')\mathrm{d}t' \tag{5}$$

where $G_\Phi(t)$ is the impulse or Green function (e.g., Livesley, 1989) which describes the response of the system to a change in forcing at $t = 0$. The forcing $F(t')$ and $\Phi(t)$ are perturbations relative to an equilibrium (climate) state.

8.19 The formulation that has been presented by Sausen and Schumann (2000) has been rearranged to include the efficacy of the perturbation, i.e.:

$$\Delta T_i(t) = r_i \lambda_{CO_2} \int_{t_0}^{t} \hat{G}_T(t - t')RF_i(t')\mathrm{d}t' \tag{6}$$

$$\hat{G}_T(t) = \frac{1}{\tau} e^{-t/\tau} \tag{7}$$

where ΔT_i is the temperature response (K) due to perturbation i, r_i is the associated efficacy, λ_{CO_2} is the CO_2 climate sensitivity parameter ($K/W\ m^{-2}$) of the parent GCM and RF_i is the associated RF ($W\ m^{-2}$). In the revised Green's function, $\hat{G}_T(t)$, τ is the lifetime (e-folding time) of a temperature perturbation (years). The current version of the model was tuned to reproduce the transient behaviour of the full-scale atmospheric ocean model ECHAM4/OPYC3 (Roeckner *et al.*, 1999), giving values for λ_{CO_2} of 0.64 $K/W\ m^{-2}$ and τ of 37.4 years. It should be noted that the heat capacity of the climate system, as expressed through λ_{CO_2} and τ, is uncertain. It is this uncertainty that results in a range of different temperature responses given by the IPCC (2007) for a particular emissions scenario.

Methodologies for calculating changes in atmospheric composition and cloudiness

8.20 The purpose of the climate-response model is to calculate the time-evolved RF and resultant global mean temperature response in a simplified and economical way. It relies on more complex models for calculating RF from changes in atmospheric composition and cloudiness, and some specimen outputs from such models are also presented here in order to show the spatial nature of the changes and their RF response. We show results from two different global models. ECHAM5/MESSy1-MADE (Lauer *et al.*, 2007) was used to calculate changes in abundances of aerosols and resultant cloud properties, and MOZART v2 (Horowitz *et al.*, 2003) was used to calculate the impacts of emissions of O_3 precursors from shipping on changes in abundance of O_3 and lifetime of CH_4.

8.21 ECHAM5/MESSy1-MADE (hereafter referred to as E5/M1-MADE) is a global aerosol model which is described in detail by Lauer *et al.* (2007). The core of E5/M1-MADE consists of the general circulation model (GCM) ECHAM5 (Roeckner *et al.*, 2006) within the framework of the Modular Earth Submodel System MESSy (Jöckel *et al.*, 2005). The aerosol submodel MADE (Ackermann *et al.*, 1998) takes into account detailed microphysical processes within aerosols. The aerosols are interactively coupled to the chemistry submodel MECCA (Sander *et al.*, 2005) as well as to the GCM's cloud microphysics (Lohmann *et al.*, 1999; 2002) and radiation scheme.

8.22 MOZART v2 is a global model of the chemistry of the troposphere. Trace species are emitted within a three-dimensional grid and advected according to prescribed wind-fields, with a time step of six hours over the course of (typically) one year. As the species are advected, they are allowed to react chemically with other species and to be removed by physical processes of wet and dry deposition. By running the model with and without shipping emissions, this allows the quantification of how emissions from shipping affect concentrations of O_3 and of CH_4 (which are the main species of radiative importance in relation to emissions of NO_x and of other precursors of ozone). The model and its performance have been described in detail by Horowitz *et al.* (2003). In the simulations that were run for this study, we used the emissions of NO_x, NMVOCs and CO given here in gridded form, over the course of one year. Meteorological data were taken from ECMWF operational data for the year 2003; this is a meteorologically "typical" year of the decade 1998–2008 and thus does not introduce any particular bias.

RESULTS: RADIATIVE FORCING AND TEMPERATURE RESPONSE

Radiative impacts of CO_2 emissions

8.23 Emissions of CO_2 have a long residence time in the atmosphere and become well mixed. Equation (5) uses the changes in concentrations of CO_2 to calculate the resultant RF. These results are presented as a time-series for the historical and present-day forcing arising from the corresponding estimations of emissions, and a range of outcomes according to the emission scenarios.

8.24 The RF of CO_2 from shipping in 2007 was 49 mW m^{-2}. For comparison, aviation has a similar – if slightly smaller – present-day annual emission rate (733 Tg of CO_2 from aviation in 2005, *cf.* 956 Tg of CO_2 from shipping for 2005) but the RF from aviation for 2007 is 30 mW m^{-2} (extrapolated from the results for 2005 of Lee *et al.*, 2009b). The somewhat larger forcing from shipping in this comparison can easily be explained by both the residence time of CO_2 in the atmosphere and the time-period of the activity. CO_2 does not have a single lifetime, and, whilst 50% of an emission is removed within 30 years, 30% of it is removed only over the timescale of a few centuries, and the remaining 20% remains airborne for many thousands of years (IPCC, 2007). A recent review of carbon-cycle models showed that this long-term airborne fraction may be between 20–60% of the original emission (Archer and Brovkin, 2008). Moreover, fuelled shipping activities date back to the late 19th century, as coal-fired vessels took over from sailing ships; by contrast, significant aviation activity is usually taken to date back to 1940.

8.25 Fuglestvedt *et al.* (2008) recently examined impacts of transportation on climate, and their estimate of the RF of CO_2 emanating from shipping in 2000 was 35 mW m^{-2} (given in supporting information; see http://www.pnas.org/content/105/2/454/suppl/DC1). The corresponding RF of CO_2 for 2000 from this work is 43 mW m^{-2}, which is in good agreement with that of Fuglestvedt *et al.* (2008), considering that the work presented here is based on a more detailed analysis of emissions data.

8.26 After 2007, a number of CO_2 emission scenarios (described in Chapter 5 of this report) are assumed. Not all of the variants within the main SRES A- and B-based families have been modelled, but rather the central scenario within the families, i.e. A1FI, A1B, A1T, B1, and B2. In addition, the two scenarios which represent the overall maximum (from A1B) and minimum (from B2) were also modelled. The CO_2 emissions between 2007 and 2050 for the various scenarios are presented in Figure 7.7, and the corresponding RF in Figure 8.3.

8.27 The various main scenarios for emission of CO_2 yield RFs in 2050 of between 99 and 122 mW m^{-2}. The minimum RF in 2050 is 68 mW m^{-2} and the maximum is 152 mW m^{-2}, which illustrates the range of uncertainty arising from the emission scenarios and their underlying assumptions.

Radiative impacts of non-CO_2 emissions

8.28 Using the methodology outlined in paragraphs 8.7 to 8.22, specific non-CO_2 RF estimates from other studies are used in order to construct a time-series of these forcings, which enables a corresponding

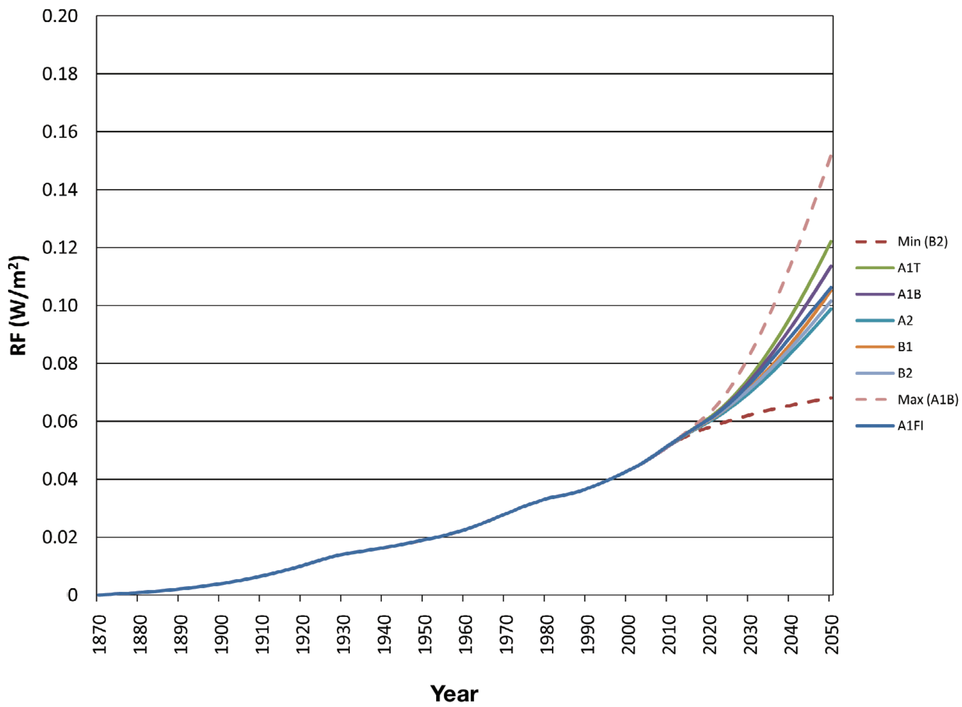


Figure 8.3 *Radiative forcing of CO_2 attributable to shipping from 1870 to 2005, and thereafter, according to a range of scenarios, to 2050*

Table 8.3 *Fuel consumption and ship emissions in 2007, as used in the model calculations. All units are teragrams per year*

Fuel use	CO_2	NO_x	SO_x	SO_4 (primary)	NMVOC*	CH_4*	BC	POM	N_2O	CO
333	1,050	24.5	14.6	0.87	0.80	0.10	0.12	0.29	0.027	1.80

* Not including tanker loading.

temperature response to be calculated (see Table 8.2). Table 8.3 shows the emissions for 2007 that have been used in the climate-response and global model simulations.

8.29 Figure 8.4 shows the RFs from CO_2 and non-CO_2 emissions as a conventional bar chart (blue bars) along with the corresponding temperature response from each forcing (red bars) for 2007. These RFs represent those arising from emissions before and during 2007. In effect, the only forcings that are influenced by emissions prior to 2007 are those for CO_2 and the reduction in CH_4 concentration. This is not the case, however, for the corresponding temperature responses, all of which are influenced by emissions prior to 2007, as explained and illustrated below.

8.30 The total global mean RF from shipping estimated from the IMO study of emissions, "tuned" to external calculations of individual non-CO_2 RFs (see Table 8.2), is -110 mW m^{-2}. The net negative RF is mostly attributable to the indirect effect, i.e. the formation of additional low-level clouds from shipping emissions, increasing the albedo of the planet and cooling the Earth's surface (Lauer *et al.*, 2007). The global mean temperature response that is implied by this negative forcing is also a cooling response in 2007.

8.31 The net negative forcing from shipping calculated by Fuglestvedt *et al.* (2008) was -71 mW m^{-2} (for 2000), whilst the equivalent net forcing calculated in this work (for 2000) was very similar, at -72 mW m^{-2}.

8.32 The picture of emissions from shipping resulting in a net negative RF and net negative global mean temperature response is a rather simplistic and potentially misleading one. This is because such an analysis ignores spatial and temporal dimensions.

8.33 The temporal dimension of different RF factors can be quite different, and the temperature response can be different again. For the short-lived emission species and effects, i.e. O_3, SO_4 direct, BC,

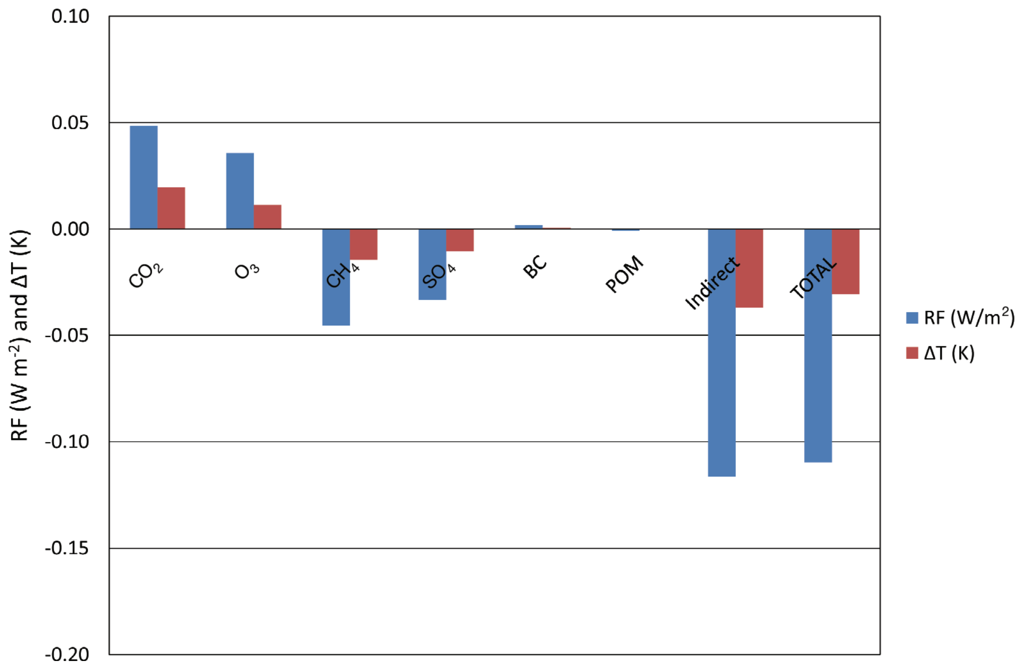


Figure 8.4 *Global mean radiative forcings (W m^{-2}) and temperature responses (K) in 2007 from shipping emissions. The figure does not include the positive RF that could possibly occur from the interaction of BC with snow, which has so far not been investigated for ships.*

POM and the indirect effect, if the emissions are removed, the forcing will disappear quickly, well within the one-year time discretization of the response model. This is not the case, however, for CO_2 and CH_4. As explained above, CO_2 has a number of lifetimes, a significant fraction of a unit emission remaining in the atmosphere for many thousands of years. Methane has a lifetime of approximately 12 years, so any perturbation to CH_4 abundance (either reduction or increase) will change the RF only slowly (in addition, there are chemical feedback effects of CH_4 on its own lifetime). The temperature response to any forcing occurs over much longer timescales because of the thermal inertia of the climate system, which is largely controlled by timescales of heat exchange between the surface ocean and the atmosphere. Thus, for a short-lived forcing which might disappear within a year, the thermal response is much longer.

8.34 The temporal responses of both RF and temperature can be illustrated by calculating the "residual" forcing and temperature response that would remain from the emissions emanating from shipping up until 2007; an alternative view of this is that it is the RF and the temperature response that would occur after 2007 if all emissions from shipping ceased. This hypothetical situation is useful as a way of illustrating the timescales of various responses which cannot be seen from an examination of Figure 8.4.

8.35 Figure 8.5 shows two snapshots of the residual RF and temperature responses arising from shipping emissions to 2007, in 2050 and in 2100.

8.36 In 2050, the residual RF has already switched from negative to positive but the temperature effect is still negative. This is because the RF from CO_2 decays only slowly but there is still a strong long-lasting negative temperature effect, which is dominated by a large negative forcing component (indirect effect). By 2100, both the residual RF and the temperature responses are positive. This is because the negative residual forcing from the CH_4 reduction has disappeared, with a persistent positive forcing from the CO_2; similarly, the positive temperature effect from CO_2 remains, whereas the negative component from the indirect effect has all but disappeared.

8.37 There are a number of ways in which the different timescales of RF and temperature response can be discussed and illustrated. The commonly used climate metric of RF is mainly a backward-looking one; i.e. it gives the RF that is produced at a given point in time from previous emissions. Such a value of RF says nothing about what may happen in the future as a result of those emissions, since, as illustrated here, a residual effect remains from long-lived greenhouse gases such as CO_2 and CH_4, and, in terms of temperature response, this may even change sign. Forward-looking metrics are used for formulation of policy and

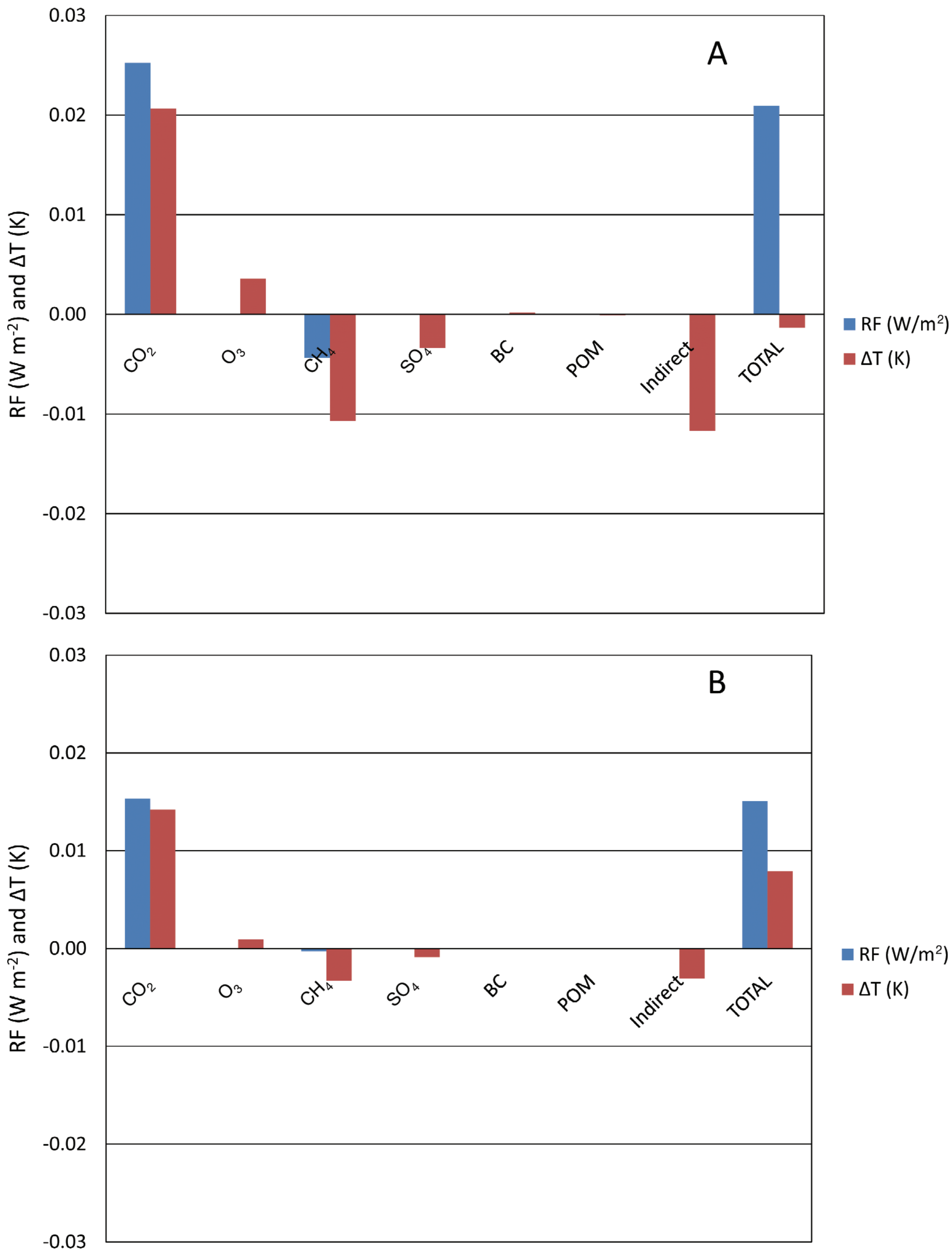


Figure 8.5 *Residual radiative forcing and temperature responses from shipping emissions to 2007 in 2050 (panel A) and 2100 (panel B). The figure does not include the positive RF that could potentially occur from the interaction of BC with snow that has, so far, not been investigated for ships.*

for assigning CO_2-equivalent (CO_2-e) emissions. Such metrics as the Global Warming Potential (GWP) or the Global Temperature change Potential (GTP; Shine *et al.*, 2005) examine the marginal impacts, at some point in the future, of a unit emission of a radiatively active species compared to that of CO_2. The Absolute GWP (AGWP) is the integrated RF over a given time horizon. These metrics are discussed in detail by Fuglestvedt *et al.* (2009). The CO_2 equivalent emissions, using the GTP metric, indicate that, after 50 years, the net global mean effect of current emissions is close to zero through the cancellation of warming by CO_2 and cooling by sulphate and nitrogen oxides (Eyring *et al.*, 2009; Fuglestvedt *et al.*, 2009).

8.38 Depending upon the exact emission scenario and the strength of rather uncertain RF responses, in particular the indirect effect, it is conceivable that the overall effect of shipping will switch from cooling to warming. This is because the persistence and accumulation of CO_2 is such that its warming effect may ultimately overwhelm any cooling effects.

8.39 The above calculations do not include the positive RF that might occur from the interaction of BC with snow (Hansen and Nazarenko, 2004; Hansen *et al.*, 2005; Koch and Hansen, 2005; Flanner *et al.*, 2007), a possibility that has not yet been investigated for ship emissions. Flanner *et al.* (2007) applied a snow, ice, and aerosol radiative model coupled to a GCM with prognostic aerosol transport, and studied the climate forcing from fossil fuel, biofuel, and biomass-burning BC emissions deposited to snow. They found that global annual mean equilibrium warming resulting from the inclusion of BC in snow is 0.1°C to 0.15°C, depending on the set of present-day emissions used, but that the annual Arctic warming is significantly larger (0.5°C to 1.621°C). The results indicate that the interaction between snow and BC could be an important component of the total BC aerosol climate forcing, in particular in the Arctic. A similar positive BC/snow forcing from ships could potentially play a major role in the Arctic in the future. The Arctic is now experiencing some of the most rapid climate changes on Earth. On average, the rate of temperature increase in the Arctic has been twice as high as in the rest of the world. Observations over the past 50 years show a decline in the extent of sea ice in the Arctic throughout the year, with the most prominent retreat in summer. The melting of Arctic sea ice will effectively unlock the Arctic Ocean area, leaving it increasingly open to human activity – particularly shipping and the production of oil and gas (IPCC, 2007; Pharand, 2007; Serreze *et al.*, 2007). The trends indicate an Arctic Ocean with longer seasons of less sea-ice cover of reduced thickness, implying that there will be improved accessibility to ships around the margins of the Arctic Basin. Climate models project an acceleration of this trend and the opening of new shipping routes and an extension of the period during which shipping is feasible. Until recently, seaborne transport of cargo in these waters has been very limited, and reported ship emissions have been low (Corbett *et al.*, 1999; Endresen *et al.*, 2003). Taking the Northern Sea Route (NSR) via the Barents Sea between Europe and the North Pacific Region can reduce travel time by up to 50%, compared to the sea routes in use today (Fridtjof Nansen Institute, 2000). Thus, if the number of navigation days increases, it is expected that more traffic will pass along this route, in which case the BC/snow effect might become an important positive radiative forcing in the future.

Spatial patterns and climate responses other than temperature

8.40 The spatial dimension is also hidden by global average mean RF and temperature responses. Long-lived greenhouse gases, such as CO_2, display only small spatial variability in their RF patterns. However, shorter-lived forcing agents, such as O_3, SO_4 aerosol and the indirect effect, have very spatially inhomogeneous forcing patterns.

8.41 In the case of NO_x emissions, the resultant O_3 forcing will have a larger spatial variability than the negative RF response of CH_4, because of the very different lifetimes (weeks versus years). The net forcing from NO_x emissions is, therefore, zero, or slightly negative through these two effects, and a global mean temperature response would also indicate either no change in global mean surface temperature from these effects or even a slight overall cooling. This is a limitation of the metric and the modelling rather than a lack of climate response. It is possible that a localized forcing is not cancelled by a homogeneous forcing of the opposite sign, even if they are of similar magnitudes at the global scale.

8.42 Determination of such localized versus global climate effects requires the use of coupled ocean–atmosphere global climate models, which are computationally expensive to run and also suffer from signal-to-noise ratio problems for small perturbations, requiring many simulations or very long equilibrium simulations. There is some evidence that the inherent feedbacks in the coupled Earth–ocean climate system result in similar spatial patterns of temperature response for different forcing patterns (Boer and Yu, 2003). However, "climate" is not temperature alone, and there is evidence that different patterns of precipitation can arise from forcings of similar magnitude but with different spatial patterns (Taylor and Penner, 1994).

8.43 In order to determine the overall RF pattern for shipping, Lee *et al.* (2009a) utilized results from the global tropospheric chemistry model MOZART v2 (which is described in paragraphs 8.20 to 8.22) for O_3 and CH_4. They also used the global aerosol model E5/M1-MADE, as described above, to simulate the zonal mean RF pattern of the direct and indirect aerosol effect, as well as a GCM for aerosol and cloudiness response and a coupled ocean–atmosphere GCM for the CO_2 response. The resulting zonal

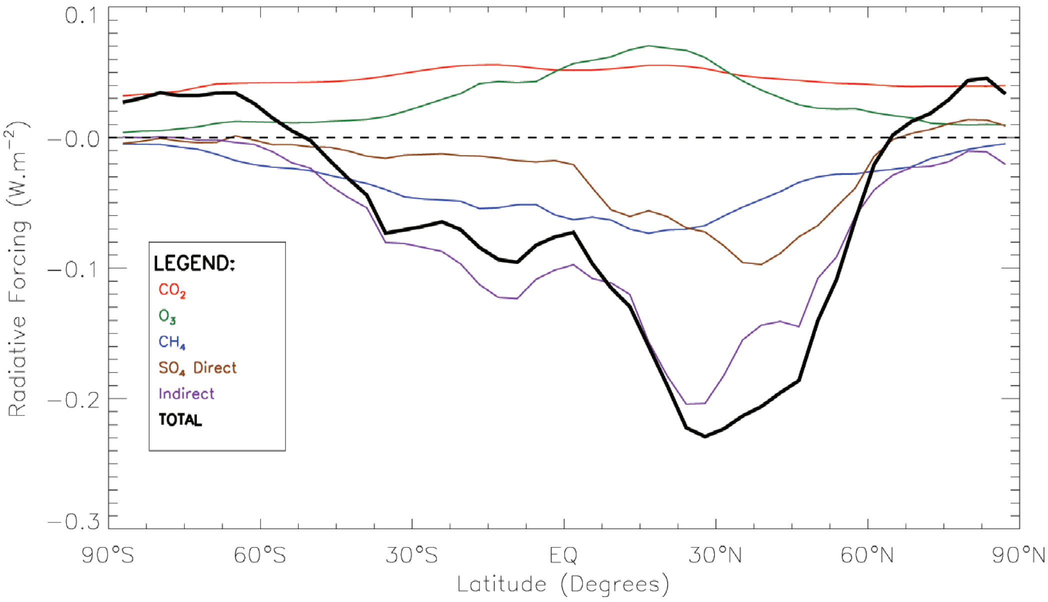


Figure 8.6 *Zonal mean annual RF pattern from shipping for the IMO estimates of RF in 2007 (modified from Lee et al., 2009a)*

mean RF pattern for the IMO estimates of RF in 2007 is shown in Figure 8.6. The results clearly demonstrate the latitudinal variation in the forcings, as described above.

SHIPPING AND CLIMATE STABILIZATION FOR CO_2

8.44 An early description of climate stabilization was given by Wigley *et al.* (1996), and has been studied by the IPCC from its Second Assessment Report (IPCC, 1996) onwards. The word "stabilization" is applied rather interchangeably to atmospheric concentrations and temperature and also inaccurately to emissions (since stabilization of emissions will not achieve stabilization of either concentrations of CO_2 or temperature within the 21st century). Strictly speaking, stabilization applies to CO_2 concentrations in the context of the so-called "WRE" (from "Wigley, Richels and Edmonds") scenarios.

8.45 Stabilization concepts and emission pathways for CO_2 are discussed because of the complicated response of the climate to CO_2. Firstly, CO_2 is well known to have a long residence time in the atmosphere, which is of the order of 300 years or more. Strictly speaking, CO_2 does not have a single lifetime because there are multiple sources and sinks, with different exchange times (see, e.g., Harvey, 2000; IPCC, 2007[3]). Secondly, in terms of temperature, the phenomenon of the thermal inertia of the climate system delays the response between emission of CO_2 and changes in temperature because of the timescales of heat exchange between the oceans and the atmosphere: this is of the order of decades. Hence, in order to limit *temperature* response, early action needs to be taken on reducing emissions in order for the climate system to respond by about 2100.

8.46 The stabilization of concentrations of atmospheric CO_2 by the end of the 21st century will require significant reductions in global emissions of CO_2 in the future. The resultant temperature from stabilizing CO_2 concentrations at various levels (e.g., 450 ppm, 550 ppm, etc.) depends on climate sensitivity. Climate sensitivity is a common test of climate models to the global mean surface temperature arising from a doubling of CO_2 concentrations. This is usually estimated to be between 2°C and 4.5°C.

8.47 A recent assessment of climate stabilization concluded that, at 550 ppm, a target of 2°C would be exceeded, and 450 ppm would result in a 50% likelihood of achieving this target (Tirpak *et al.*, 2005). More recently, Professor James Hansen, Director of NASA's Goddard Institute for Space Studies, has suggested that 350 ppm of CO_2 is a more appropriate level to avoid "dangerous climate change", which is *below* the

3 See "Frequently Asked Questions 7.1 (http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Print_FAQs.pdf) accessed 6 August 2008

current atmospheric levels of CO_2 of 385 ppm (Hansen *et al.*, 2008). This assertion is based on analyses of palaeoclimate data.

8.48 In order to achieve the more frequently discussed stabilization goal of 450 ppm of CO_2, global emissions of CO_2 must be limited to the values shown in WRE 450 in Figure 8.7; similarly, the WRE 550 emission trajectory is also shown.

8.49 The following paragraphs discuss the concept of CO_2 stabilization pathways in the context of the shipping emission scenarios developed for this work. It is important to note that this is merely illustrative: the shipping emission scenarios in this report inherently assume no climate-policy intervention (as is the case with the SRES background scenario storylines of the IPCC). Thus, a stabilization scenario clearly represents climate-policy intervention, so that the two "storylines" are inherently different.

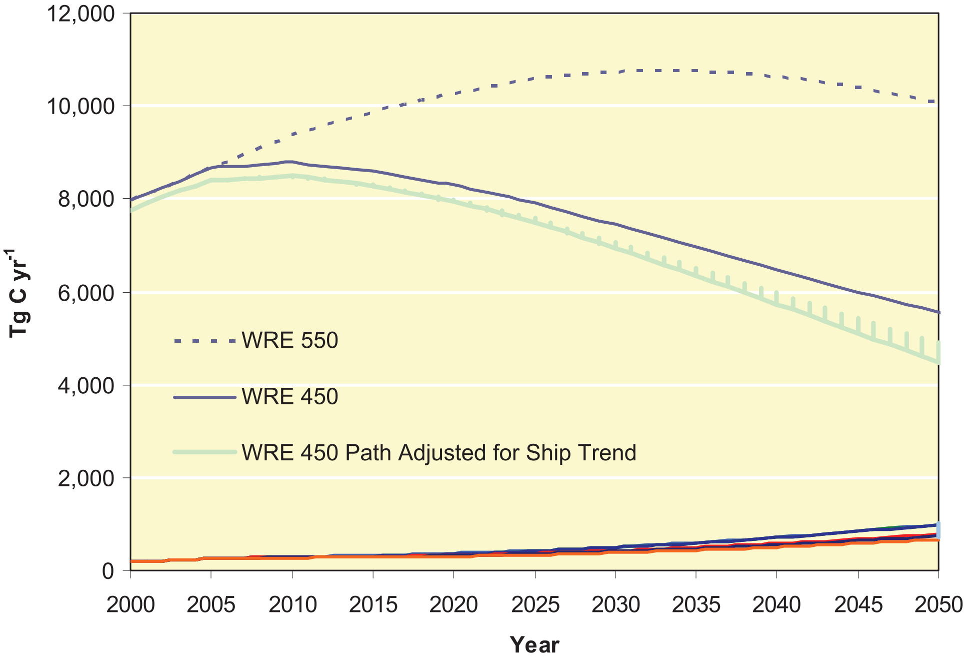


Figure 8.7 *Comparison of modelled shipping emissions, curves for WRE 450 and WRE 550, and WRE 450 adjusted for ship emissions (global total minus the emissions arising from shipping)*

8.50 Figure 8.7 illustrates the potential conflict between the predicted growth in emissions from shipping under scenarios that assume no climate-intervention policy and the stabilization of CO_2 in the atmosphere at 450 ppm. As Figure 8.7 shows, the predicted emissions from shipping in 2050 in the base scenarios would comprise 12–18% of the total emissions for the WRE 450 scenario at that date (see also Table 8.4).

Table 8.4 *Emissions from shipping, as a share of global total, as per WRE scenarios, in 2050*

	A1FI	A1B	A1T	A2	B1	B2
WRE 450	17.6%	17.9%	17.8%	14.1%	13.4%	12.0%
WRE 550	9.7%	9.9%	9.8%	7.8%	7.4%	6.6%

8.51 The WRE stabilization scenarios are not prescriptive as far as the make-up of the emissions is concerned, since they are were obtained by inverse modelling to achieve stabilized concentrations of CO_2 in the atmosphere. The shipping scenarios that are presented in this report are based on SRES-type assumptions, which are not climate-intervention policy scenarios *cf.* the WRE scenarios, and are thus not compatible in philosophy. Nonetheless, it is useful to present the SRES-based projections of emissions from shipping in the context of the stabilization of emissions pathways, in order to illustrate that, if shipping is to play a role in stabilization, it is highly likely that reductions over and above those projected will be necessary.

IMPACT ON HUMAN HEALTH

8.52 At local and regional scales, ocean-going ships impact human health through the formation and transport of ground-level ozone and emissions of sulphur and particulate matter (Corbett *et al.*, 2007). In many harbour cities, ship emissions are a dominant source of urban pollution. Furthermore, emissions of NO_x, CO, VOC, particles and sulphur (and their derivative species) from ships may be transported in the atmosphere over several hundred kilometres, and can contribute to air-quality problems further inland, even if they are emitted at sea. This pathway is especially relevant to the deposition of sulphur and nitrogen compounds, which cause acidification/eutrophication of natural ecosystems and freshwater bodies and threaten biodiversity through excessive nitrogen inputs (Eyring *et al.*, 2007b; 2009). For this reason, control of NO_x, SO_2 and particle emissions will have beneficial impacts on air quality, acidification and eutrophication.

8.53 Corbett *et al.* (2007) demonstrated that emissions of PM from ocean-going ships could cause approximately 60,000 premature mortalities annually from cardiopulmonary disease and lung cancer. This value is expected to increase by 40% by 2012 in their scenarios, which do not include the new amendments to the regulations of MARPOL Annex VI, to reduce harmful emissions from ships that were adopted by the Marine Environment Protection Committee (MEPC) of IMO in October 2008. The mortality estimate of Corbett *et al.* (2007) does not account for additional health impacts such as respiratory illnesses (e.g., bronchitis, asthma, and pneumonia). The health impacts are particularly concentrated near coastlines in Europe, East Asia, and South Asia.

SUMMARY AND CONCLUSIONS: CLIMATE IMPACT

8.54 International shipping and its emissions produce significant impacts on atmospheric composition, human health and climate, and some of these impacts are dependent upon latitude and whether the emissions occur in coastal areas or on the open sea. For some of the compounds and their reaction products emitted from ships, the RF is positive (CO_2, O_3 and BC), while for others the forcing is negative (e.g., direct effect of sulphate particles, reduced ambient concentrations of methane). Particles may also have an indirect effect on climate through their ability to modify the optical properties of clouds by acting as cloud condensation nuclei (CCN) or by dissolving in the cloud drops and altering their surface tension (the so-called "indirect aerosol effect"). This results in the clouds being optically brighter and reflecting more solar radiation back to space. Although the associated uncertainties are still high, results from models indicate that the cooling due to altered clouds currently outweighs the warming effects from greenhouse gases (such as CO_2 or O_3) resulting from shipping, causing a net negative RF at present. However, this calculation does not include the positive RF that might occur from the interaction of BC with snow, a phenomenon that has not yet been investigated for ships.

8.55 Reductions in emissions of sulphur could result in regional reductions in the resultant negative RF. The climatic trade-off between positive and negative RF is still a topic of research, but, from what is currently known, a simple cancellation of global means is potentially inappropriate and a more comprehensive assessment metric is required. We emphasize, however, that CO_2 remains in the atmosphere for a long time and will continue to have a warming effect long after it was emitted. The IPCC Fourth Assessment Report highlighted that a significant fraction of CO_2 remains in the atmosphere for thousands of years. By contrast, sulphate has a residence time in the atmosphere of approximately 10 days, and the climate response to sulphate is of the order of decades, whilst that of CO_2 is of the order of centuries and longer. Indeed, the CO_2-equivalent emissions, using the Global Temperature Change Potential (GTP) metric, indicate that the net effect, after 50 years, of current emissions is nearly neutral through cancellation of warming by CO_2 and cooling by sulphate and NO_x (Eyring *et al.*, 2009). This is supported by the model calculations that are presented here, where the residual effects of emissions that had been released up until 2007 were examined up until 2050 and 2100. This showed that, by 2050, the net RF resulting from historical emissions of CO_2 was already positive, whereas only the negative RF effect of CH_4 remained. However, in this "ship-emissions off in 2007" scenario, the overall net temperature effect is still negative in 2050, because of the long memory of the climate system (thermal inertia of the oceans). By 2100, no significant negative forcing is simulated, but 32% of the positive 2007 RF from CO_2 still remains, nearly 100 years later. Thus, in 2100, the overall residual temperature signal and RF are both positive. These illustrative calculations demonstrate the long-lasting nature of CO_2 and its effects on the climate system.

CONCLUSIONS

8.56 The following conclusions were drawn:

1. Increases in well-mixed greenhouse-gases, such as carbon dioxide, lead to positive radiative forcing and to long-lasting global warming.
2. The RF from shipping-generated CO_2 for 2007 was calculated to be 49 mW m^{-2}. The IPCC Fourth Assessment Report estimated that the total RF from CO_2 (all sources) was 1.66 W m^{-2} (for 2005), so that shipping contributed approximately 2.8% to the total anthropogenic CO_2 RF in 2005.
3. For a range of 2050 scenarios, the shipping CO_2 RF was calculated to be between 99 and 122 mW m^{-2}, bounded by a minimum/maximum uncertainty range (from the scenarios) of 68 mW m^{-2} and 152 mW m^{-2}.
4. The total RF for 2007 from shipping was estimated to be −110 mW m^{-2}, dominated by a rather uncertain estimate of the indirect effect (−116 mW m^{-2}) and not including the possible positive RF from the interaction of BC with snow, an effect that has not yet been calculated for ships. We also emphasize that CO_2 remains in the atmosphere for a long time and will continue to have a warming effect long after it has been emitted. This has been demonstrated here by showing that the residual effect from shipping emissions up to 2007 turns from a negative effect on temperature to a positive effect on temperature. By contrast, sulphate has a residence time in the atmosphere of approximately 10 days, and the climate response from sulphate is of the order of decades, whilst that of CO_2 is of the order of centuries to millennia.
5. Simple calculations of values of global mean have been presented here for RF and temperature response, and are in agreement with other published work (e.g., Fuglestvedt *et al.*, 2008). As highlighted by others, global mean temperature response is only a first-order indicator of climate change. Calculations presented here show that forcings caused by shipping have a complex spatial structure, and there is evidence from other, more general, studies of indirect cloud-forcing effects that significant changes in precipitation patterns may result from localized negative RFs, even if the localized temperature response is not so variable. Such precipitation changes, even from negative forcings, constitute climate change. This is a complex subject and more work on this aspect is needed.
6. While the control of NO_x, SO_2 and particle emissions from ships will have beneficial impacts on air quality, on acidification and on eutrophication, reductions of CO_2 emissions from all sources, including ships and other freight modes, are required to reduce global warming. Moreover, a shift to cleaner combustion and cleaner fuels may be enhanced by a shift to technologies that result in the lowering of the amount of CO_2 that is released from each unit of fuel that is used.
7. Climate stabilization will require significant reductions in future global emissions of CO_2. The emissions from shipping for 2050 that have been developed for this work – which are based on SRES non-climate-intervention policy assumptions – constitute 12 to 18% of the WRE 450 scenario, which corresponds to the total global CO_2 emissions permissible in 2050 if the increase in global average temperature is to be limited to 2°C with a probability greater than 50%.

ACKNOWLEDGEMENTS

8.57 We thank Jerome Hilaire (MMU, UK), Axel Lauer (University of Hawaii, USA), Michael Ponater (DLR, Germany) and Ruben Rodriguez (MMU, UK) for performing the global model simulations and zonal mean annual RF estimates from shipping. They are displayed in figure 8.6 of this report.

REFERENCES

1 Ackermann, I.J., Hass, H., Memmesheimer, M., Ziegenbein, C. and Ebel, A. 1998. "Modal aerosol dynamics for Europe: Development and first applications". *Atmospheric Environment*, 32: 2981–2999.

2 Archer, D. and Brovkin, V. 2008. "The millennial atmospheric lifetime of anthropogenic CO_2". *Climatic Change*, 90: 283–297, doi:10.1007/s10584–008–9413–1.

3 Boer, G.J. and Yu, B. 2003. "Climate sensitivity and climate state". *Climate Dynamics*, 21: 167–176.

4 Corbett, J.J. 2003. "New directions: Designing ship emissions and impacts research to inform both science and policy". *Atmospheric Environment*, 37: 4719–4721.

5 Corbett, J.J., Fischbeck, P.S. and Pandis, S.N. 1999. "Global nitrogen and sulphur inventories for oceangoing ships". *Journal of Geophysical Research*, 104(3): 3457–3470.

6 Corbett, J.J., Winebrake, J.J., Green, E.H., Kasibhatla, P., Eyring, V. and Lauer, A. 2007. "Mortality from ship emissions: A global assessment". *Environmental Science & Technology*, 41: 8512–8518, doi:10.1021/es071686z.

7 Davis, D.D., Grodzinsky, G., Kasibhatla, P., Crawford, J., Chen, G., Liu, S., Bandy, A., Thornton, D., Guan, H. and Sandholm, S. 2001. "Impact of ship emissions on marine boundary layer NO_x and SO_2 distributions over the Pacific Basin". *Geophysical Research Letters*, 28: 235–238.

8 Durkee, P.A., Chartier, R.E., Brown, A., Trehubenko, E.J., Rogerson, S.D., Skupniewicz, C., Nielsen, K.E., Platnick, S. and King, M.D. 2005. "Composite ship track characteristics". *Journal of Atmospheric Science*, 57: 2542–2553.

9 Endresen, Ø., Sørgård, E., Sundet, J.K., Dalsøren, S.B., Isaksen, I.S.A., Berglen, T.F. and Gravir, G. 2003. "Emissions from international sea transportation and environmental impact". *Journal of Geophysical Research*, 108(D17): 4560, doi:10.1029/2002JD002898.

10 Endresen, Ø., Sørgård, E., Behrens, H.L., Brett, P.O. and Isaksen, I.S.A. 2007. "A historical reconstruction of ships' fuel consumption and emissions". *Journal of Geophysical Research*, 112: D12301, doi:10.1029/2006JD007630.

11 Eyring, V., Stevenson, D.S., Lauer, A., Dentener, F.J., Butler, T., Collins, W.J., Ellingsen, K., Gauss, M., Hauglustaine, D.A., Isaksen, I.S.A., Lawrence, M., Richter, A., Rodriguez, J.M., Sanderson, M., Strahan, S.E., Sudo, K., Szopa, S., van Noije, T.P.C. and Wild, O. 2007a. "Multi-model simulations of the impact of international shipping on atmospheric chemistry and climate in 2000 and 2030". *Atmospheric Chemistry and Physics*, 7: 757–780.

12 Eyring, V., Corbett, J.J., Lee, D.S. and Winebrake, J.J. 2007b. "Brief summary of the impact of ship emissions on atmospheric composition, climate, and human health". Health and Environment Sub-Group of the International Maritime Organization: London, UK, 6 November 2007.

13 Eyring, V., Isaksen, I.S.A., Berntsen, T., Collins, W.J., Corbett, J.J., Endresen, O., Grainger, R.G., Moldanova, J., Schlager, H. and Stevenson, D.S. 2009. "Transport impacts on atmosphere and climate: Shipping". *Atmospheric Environment*, under revision.

14 Fearnleys. 2007. *Fearnleys Review 2007, The Tanker and Bulk Markets and Fleets*, Oslo.

15 Flanner, M.G., Zender, C.S., Randerson, J.T. and Rasch, P.J. 2007. "Present-day climate forcing and response from black carbon in snow". *Journal of Geophysical Research*, 112: D11202, doi:10.1029/2006JD008003.

16 Forster, P., Ramaswamy, V., Artaxo, P., Berntsen, T., Betts, R., Fahey, D.W., Haywood, J., Lean, J., Lowe, D.C., Myhre, G., Nganga, J., Prinn, R., Raga, G., Schulz, M. and Van Dorland, R. 2007. "Changes in atmospheric constituents and in radiative forcing". In *'Climate Change', Fourth Assessment Report of Working Group I of the Intergovernmental Panel on Climate Change*, Cambridge University Press, Cambridge, UK.

17 Fridtjof Nansen Institute (FNI). 2000. "Northern Sea Route Cargo Flows and Infrastructure – Present State and Future Potential". FNI REPORT 13/2000. ISBN 82–7613–400–9. Fridtjof Nansen Institute, PO Box 326, N-1326 Norway.

18 Fuglestvedt, J.S., Berntsen, T., Myhre, G., Rypdal, K. and Bieltvedt Skeie, R. 2008. "Climate forcing from the transport sectors". *Proceedings of the National Academy of Sciences USA*, 105: 454–458.

19 Fuglestvedt, J.S., Shine, K.P., Cook, J., Berntsen, T., Lee, D.S., Stenke, A., Bieltvedt Skeie, R., Velders, G.J.M. and Waitz, I.A. 2009. "Transport impacts on atmosphere and climate: metrics". *Atmospheric Environment*, under revision.

20 Hansen, J. and Nazarenko, L. 2004. "Soot climate forcing via snow and ice albedos". *Proceedings of the National Academy of Sciences USA*, 101: 423–428, doi:10.1073/pnas.2237157100.

21 Hansen, J., *et al.* 2005. "Efficacy of climate forcings". *Journal of Geophysical Research*, 110: D18104.

22 Hansen, J., Sato, M., Kharecha, P., Beerling, D., Berner, R., Masson-Delmotte, V., Pagani, M., Raymo, M., Royer, D.L. and Zachos, J.C. 2008. "Target atmospheric CO_2: where should humanity aim?" Manuscript online http://arxiv.org/abs/0804.1126 (accessed 6 August 2008).

23 Harvey, L.D.D. 2000. *Global Warming: the hard science*. Prentice Hall, London.

24 Hasselmann K., Sausen, R., Maier-Reimer, E. and Voss, R. 1993. "On the cold start problem in transient simulations with coupled atmosphere-ocean models". *Climate Dynamics*, 9: 53–61.

25 Hasselmann K., Hasselmann, S., Giering, R., Ocana, V. and von Storch, H. 1997. "Sensitivity study of optimal CO_2 emission paths using a Simplified Structural Integrated Assessment Model (SIAM)". *Climatic Change*, 37: 345–386.

26 Horowitz, L.W., Walters, S., Mauzerall, D.L., Emmons, L.K., Rasch, P.J., Granier, C., Tie, X., Lamarque, J.-F., Schultz, M.G., Tyndall, G.S., Orlando, J.R. and Brasseuer, G.P. 2003. "A global simulation of tropospheric ozone and related tracers: Description and evaluation of MOZART, version 2". *Journal of Geophysical Research*, 108(D24): 4784, doi:10.1029/2002JD002853.

27 IPCC (Intergovernmental Panel on Climate Change). 1996. Climate Change 1995: the science of climate change. Contribution of Working Group I to the Second Assessment of the Intergovernmental Panel on Climate Change. Houghton, J.T., Meira Filho, L.G., Callender, B.A., Harris, N., Kattenberg, A. and Maskell, K. (eds). Cambridge University Press, Cambridge, UK. 572 pp.

28 IPCC, 1999. *Aviation and the Global Atmosphere*. Penner, J.E., Lister, D.H., Griggs, D.J., Dokken, D.J. and McFarland, M. (eds), Intergovernmental Panel on Climate Change, Cambridge University Press, Cambridge, UK.

29 IPCC (Intergovernmental Panel on Climate Change). 2000. *Emission Scenarios. A Special Report of IPCC Working Group III*, Cambridge University Press, Cambridge, UK.

30 IPCC. 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. Solomon, S., Qin, D., Manning, M., Chen, Z., Marquis, M., Averyt, K.B., Tignor, M. and Miller, H.L. (eds). Cambridge University Press, Cambridge, UK and New York, USA.

31 Jöckel, P., Sander, R., Kerkweg, A., Tost, H. and Lelieveld, J. 2005. "Technical Note: The Modular Earth Submodel System (MESSy) – a new approach towards Earth System Modeling". *Atmospheric Chemistry and Physics*, 5: 433–444.

32 Kasibhatla, P., Levy II, H., Moxim, W.J., Pandis, S.N., Corbett, J.J., Peterson, M.C., Honrath, R.E., Frost, G.J., Knapp, K., Parrish, D.D. and Ryerson, T.B. 2000. "Do emissions from ships have a significant impact on concentration of nitrogen oxides in the marine boundary layer?" *Geophysical Research Letters*, 27: 2229–2233.

33 Koch, D. and Hansen, J. 2005. "Distant origins of Arctic black carbon: A Goddard Institute for Space Studies ModelE experiment". *Journal of Geophysical Research*, 110: D04204, doi:10.1029/2004JD005296.

34 Lauer, A., Eyring, V., Hendricks, J., Jöckel, P. and Lohmann, U. 2007. "Global model simulations of the impact of ocean-going ships on aerosols, clouds, and the radiation budget". *Atmospheric Chemistry and Physics*, 7: 5061–5079.

35 Lawrence, M.G. and Crutzen, P.J. 1999. "Influence of NO_x emissions from ships on tropospheric photochemistry and climate". *Nature*, 402: 167–170.

36 Lee, D.S., Lim, L.L, Eyring, V., Sausen, R., Endresen, Ø. and Behrens, H.L. 2007. "Radiative forcing and temperature response from shipping". In *Transport, Atmosphere and Climate*, Sausen, R., Lee, D.S. and Fichter, C. (eds). Oxford, 26–29 June, 2006. European Commission Air Pollution Report, 208–213.

37 Lee, D.S., Eyring, V., Hilaire, J., Lauer, A., Lim, L.L., Ponater, M. and Rodriguez, R. 2009a. "Radiative forcing from shipping emissions: spatial and zonal mean responses". Manuscript in preparation.

38 Lee, D.S., Fahey, D., Forster, P., Newton, P.J., Wit, R.C.N., Lim, L.L., Owen, B. and Sausen, R. 2009b. "Aviation and global climate change in the 21st Century". *Atmospheric Environment*, under revision.

39 Lim, L.L., Lee, D.S., Sausen, R. and Ponater, M. 2007. "Quantifying the effects of aviation on radiative forcing and temperature with a climate response model". In *Transport, Atmosphere and Climate*, Sausen, R., Lee, D.S. and Fichter, C. (eds). Proceedings of an international conference, Oxford, 26–29 June 2006. European Commission Air Pollution Report, 202–207.

40 Livesey, R.K. 1989. *Mathematical Methods for Engineers*. Ellis Horwood Limited, Chichester, UK.

41 Lohmann, U., Feichter, J., Chuang, C.C. and Penner, J.E. 1999. "Prediction of the number of cloud droplets in the ECHAM GCM". *Journal of Geophysical Research*, 104: 9169–9198.

42 Lohmann, U. 2002. "Possible aerosol effects on ice clouds via contact nucleation". *Journal of Atmospheric Science*, 59: 647–656.

43 Meier-Reimer, E. and Hasselmann, K. 1987. "Transport and storage of CO_2 in the ocean – an inorganic ocean-circulation carbon cycle model". *Climate Dynamics*, 2: 63–90.

44 Myhre, G., Highwood, E.J., Shine, K.P. and Stordal, F. 1998. "New estimates of radiative forcing due to well mixed greenhouse gases". *Geophysical Research Letters*, 25: 2715–2718.

45 Pharand, D. 2007. "The Arctic waters and the Northwest Passage: a final revisit". *Ocean Development and International Law*, 38: 3–69, doi:10.1080/00908320601071314.

46 Ramaswamy, V., Chanin, M.L., Angell, J., Barnett, J., Gaffen, D., Gelman, M., Keckhut, P., Koshelkov, Y., Labitzke, K., Lin, J.J.R., O'Neil, A., Nash, J., Randel, W., Rood, R., Shine, K., Shiotani, M. and Swinbank, R. 2001. "Stratospheric temperature trends: Observations and model simulations". *Reviews of Geophysics*, 39: 71–122.

47 Roeckner, E., Brokopf, R., Esch, M., Giorgetta, M., Hagemann, S., Kornblueh, L., Manzini, E., Schlese, U. and Schulzweida, U. 2006. "Sensitivity of simulated climate to horizontal and vertical resolution in the ECHAM5 atmosphere model". *Journal of Climate*, 19: 3771–3791.

48 Sander, R., Kerkweg, A., Jöckel, P. and Lelieveld, J. 2005. "Technical Note: The new comprehensive atmospheric chemistry module MECCA". *Atmospheric Chemistry and Physics*, 5: 445–450.

49 Sausen, R. and Schumann, U. 2000. "Estimates of the climate response to aircraft CO_2 and NO_x emissions scenarios". *Climatic Change*, 44: 27–58.

50 Schreier, M., Kokhanovsky, A.A., Eyring, V., Bugliaro, L., Mannstein, H., Mayer, B., Bovensmann, H. and Burrows, J.P. 2006. "Impact of ship emissions on the microphysical, optical and radiative properties of marine stratus: a case study". *Atmospheric Chemistry and Physics*, 6: 4925–4942.

51 Schreier, M., Mannstein, H., Eyring, V. and Bovensmann, H. 2007. "Global ship track distribution and radiative forcing from one year of AATSR data". *Geophysical Research Letters*, 34: L17814, doi:10.1029/2007GL030664.

52 Serreze, M.C, Holland, M.M. and Stroeve, J. 2007. "Perspectives on the Arctic's shrinking sea-ice cover". *Science*, 315: 1533–1536, doi:10.1126/science.1139426.

53 Shine, K.P., Fuglestvedt, J.S., Hailemariam, K. and Stuber, N. 2005. "Alternatives to the global warming potential for comparing climate impacts of emissions of greenhouse gases". *Climatic Change*, 68: 281–302.

54 Taylor, K.E. and Penner, J.E. 1994. "Response of the climate system to atmospheric aerosols and greenhouse gases". *Nature*, 369: 734–737.
55 Tirpak D., Ashton, J., Dadi, Z., Meira Filho, L.G., Metz, B., Parry, M., Schellnhuber, J., Yap, K.S., Watson, R. and Wigley, T. 2005. "Avoiding dangerous climate change. International symposium on the stabilisation of greenhouse gas concentrations. Report of the International Scientific Steering Committee". http://www.stabilisation2005.com/Steering_Commitee_Report.pdf (accessed 30 June 2008).
56 Wigley, T.M.L., Richels, R. and Edmonds, J.A. 1996. "Economic and environmental choices in the stabilisation of atmospheric CO_2 concentrations". *Nature*, 379: 242–245.

9

Comparison of emissions of CO_2 from ships with emissions from other modes of transport

INTRODUCTION

9.1 This chapter contains estimates of the transport efficiency of cargo ships, based on the CO_2 emission inventory calculations and assumptions regarding average utilization of cargo-carrying capacity. The figures are compared with similar figures for other modes of transport. Information on progress that has been made in terms of improving efficiency is also given.

DEFINITIONS AND METHODOLOGY

9.2 The CO_2 emission efficiency of transport can be expressed as CO_2/tonne*kilometre, where "CO_2" expresses the total mass of emission from the activity (measured in grams) and "tonne*kilometre" (measured as tonne-kilometres) expresses the total transport work.

9.3 For a given period, the CO_2 emission efficiency is then defined as:

$$CO_2 \text{ efficiency} = \frac{CO_2}{\text{tonne} * \text{kilometre}}$$

where:

CO_2 = total CO_2 emitted from the vehicle within the period

tonne*kilometre = total actual number of tonne-kilometres of work done within the same period

The principle can be applied in all transport sectors, such as shipping, rail, road and aviation. Using this definition, it is implied that all emissions of CO_2 from a vehicle that occur within the reporting period are counted, whether or not the train, ship, lorry or other carrier is loaded with goods. It is also implied that the CO_2 efficiency will be dependent on the load factor, i.e. the amount of cargo that is actually carried when loaded. This principle is upheld in the Energy Efficiency Design Index (EEDI), and also in the Energy Efficiency Operational Indicator (EEOI).

9.4 It should be noted that there are other definitions of CO_2 efficiency that also result in units of grams of CO_2 per tonne-kilometre. For instance, calculations can be made which show the efficiency of transport when fully loaded, i.e. not accounting for average loading factors and empty running. For this reason, figures that are published in other sources may be very different from those presented here. It is, therefore, necessary to ensure that the same definitions are used when comparisons are made. In the case of shipping, nautical miles are frequently used for distance, in which case CO_2 efficiency can be measured as grams of CO_2/tonne-mile. To convert from grams of CO_2/tonne-mile to grams of CO_2/tonne-km, one must multiply by 0.540.

COMPARISON OF THE CO_2 EFFICIENCY OF TRANSPORT MODES

CO_2 efficiency of transport by sea

9.5 In order to assess the transport efficiency of the various segments of the world cargo fleet, estimates of CO_2 emissions from the 2007 inventory are used as a starting point; however, it is also necessary, in addition, to estimate the transport work (tonne-kilometres) that is being done by each segment in the fleet. For this study, the kilometres were estimated, based on the average service speed of each category of vessel from the Fairplay database and the number of main engine operating days (days at sea) from the 2007 inventory. The CO_2 efficiency does not depend on the assumed number of main engine operating days since the amount of CO_2 that is emitted is also proportional to the number of operating days; therefore these cancel each other. The numbers of tonnes transported were estimated as the product of the assessed cargo weight capacity of the ship and the assessed average utilization factor. The average utilization factor takes into account the degree to which various ships typically need to do empty repositioning (ballast) voyages, multiple port deliveries as well as typical capacity utilization when loaded. Shortage of demand, where there is not enough cargo to fill the ship, is not considered, although in reality this is common, due to seasonal variations, degree of competition and fluctuations in world trade.

9.6 When estimating cargo weight capacity, a net weight of 7 tonnes per cargo container has been used for container ships. For ro–ro ships, a weight of 2 tonnes/lane metre is used, while 1.5 tonnes per car equivalent unit is used for pure car carriers. Results from the calculation are shown in Table 9.1.

9.7 The figures in Table 9.1 are intended to indicate realistic levels of transport efficiencies of various categories of ships. The actual values of individual ships and annual averages will depend on a range of factors, including fluctuation in trade demand. This latter effect is illustrated in Figure 9.1, using fleet productivity data from UNCTAD [1]. This figure shows that the ratio of estimated seaborne trade (in tonne-miles) to fleet transport capacity (as indicated by deadweight tonnage) can vary significantly from one year to the next. This will result in variations in a number of parameters, including days at sea, speed and cargo utilization factors.

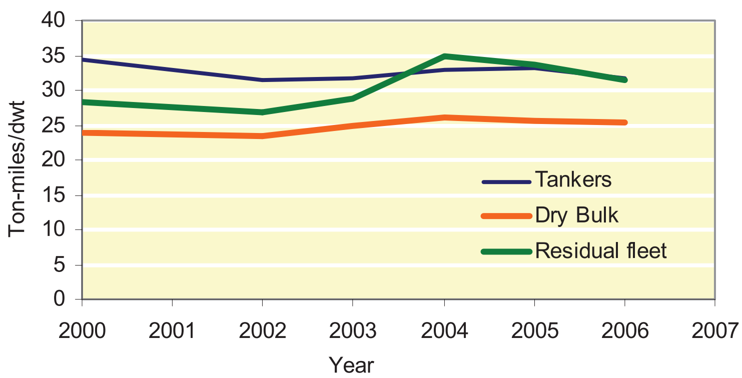


Figure 9.1 *Fleet productivity data, based on data from UNCTAD [1]*

CO_2 efficiency of road transport

9.8 The transport efficiency of vehicles on roads is affected by many of the same factors as that in shipping, i.e. the efficiency will depend significantly on the load factor, efficiency of the vehicle and cargo type; heavier cargo and larger vehicles will improve the cargo/vehicle weight ratio, resulting in better values of CO_2/tonne-km. But there is also an important difference, since legislation in most of the world limits the total weight of the truck and trailer unit. The consequence of this is that, even with quite low-density cargoes (down to 350 kg/m^3), the full payload capacity of the road unit can, in general, be fully utilized. Short- and long-distance transport has different characteristics. Short-distance transports will mainly be in urban areas, and the road vehicles will more often go one way with goods and back empty. The long-distance transports will partly go into urban areas, but this type of traffic will more often be on uncongested highways/motorways. Due to the long distances that are travelled, focus will be on utilizing the capacity both ways. Transport in areas with steep hills, winding roads and/or heavy traffic will contribute to increased consumption of fuel. A detailed study of emissions from road vehicles has not been undertaken; however, efficiency data that are comparable to the data for ships have been retrieved from the literature, as shown in Table 9.2. From these figures, it is concluded that the efficiency of transport of road freight ranges from 80 to 180 grams of CO_2/tonne-km, with a typical average value of 150. Naturally, the variation in efficiency between individual trucks is much wider than what is indicated in the range of averages shown in Table 9.2.

Table 9.1 *Estimates of CO_2 efficiency for cargo ships*

Type	Size	Average cargo capacity (tonne)	Average yearly capacity utilization	Average service speed (knots)	Transport work per ship (tonne-NM)	Loaded efficiency (g of CO_2/ tonne-km)	Total efficiency (g of CO_2/ tonne-km)
Crude oil tanker	200,000+ dwt	295,237	48%	15.4	14,197,046,742	1.6	2.9
Crude oil tanker	120,000–199,999 dwt	151,734	48%	15.0	7,024,437,504	2.2	4.4
Crude oil tanker	80,000–119,999 dwt	103,403	48%	14.7	4,417,734,613	3.0	5.9
Crude oil tanker	60,000–79,999 dwt	66,261	48%	14.6	2,629,911,081	4.3	7.5
Crude oil tanker	10,000–59,999 dwt	38,631	48%	14.5	1,519,025,926	5.2	9.1
Crude oil tanker	0–9,999 dwt	3,668	48%	12.1	91,086,398	20.7	33.3
Products tanker	60,000+ dwt	101,000	55%	15.3	3,491,449,962	3.3	5.7
Products tanker	20,000–59,999 dwt	40,000	55%	14.8	1,333,683,350	7.2	10.3
Products tanker	10,000–19,999 dwt	15,000	50%	14.1	464,013,471	11.3	18.7
Products tanker	5,000–9,999 dwt	7,000	45%	12.8	170,712,388	14.8	29.2
Products tanker	0–4,999 dwt	1,800	45%	11.0	37,598,072	26.5	45.0
Chemical tanker	20,000+ dwt	32,200	64%	14.7	1,831,868,715	5.7	8.4
Chemical tanker	10,000–19,999 dwt	15,000	64%	14.5	820,375,271	7.3	10.8
Chemical tanker	5,000–9,999 dwt	7,000	64%	14.5	382,700,554	10.7	15.1
Chemical tanker	0–4,999 dwt	1,800	64%	14.5	72,147,958	18.6	22.2
LPG tanker	50,000+ m^3	46,656	48%	16.6	2,411,297,106	5.2	9.0
LPG tanker	0–49,999 m^3	3,120	48%	14.0	89,631,360	27.0	43.5
LNG tanker	200,000+ m^3	97,520	48%	19.6	5,672,338,333	5.4	9.3
LNG tanker	0–199,999 m^3	62,100	48%	19.6	3,797,321,655	8.4	14.5
Bulk carrier	200,000+ dwt	227,000	50%	14.4	10,901,043,017	1.5	2.5
Bulk carrier	100,000–199,999 dwt	163,000	50%	14.4	7,763,260,284	1.8	3.0
Bulk carrier	60,000–99,999 dwt	74,000	55%	14.4	3,821,361,703	2.7	4.1
Bulk carrier	35,000–59,999 dwt	45,000	55%	14.4	2,243,075,236	3.8	5.7
Bulk carrier	10,000–34,999 dwt	26,000	55%	14.3	1,268,561,872	5.3	7.9
Bulk carrier	0–9,999 dwt	2400	60%	11.0	68,226,787	22.9	29.2
General cargo	10,000+ dwt	15,000	60%	15.4	866,510,887	7.6	11.9
General cargo	5,000–9,999 dwt	6,957	60%	13.4	365,344,150	10.1	15.8
General cargo	0–4,999 dwt	2,545	60%	11.7	76,945,792	10.9	13.9
General cargo	10,000+ dwt, 100+ TEU	18,000	60%	15.4	961,054,062	8.6	11.0
General cargo	5,000–9,999 dwt, 100+ TEU	7,000	60%	13.4	243,599,799	13.8	17.5
General cargo	0–4,999 dwt, 100+ TEU	4,000	60%	11.7	120,938,043	15.5	19.8
Refrigerated cargo	All	6,400	50%	20.0	392,981,809	12.9	12.9
Container	8,000+ TEU	68,600	70%	25.1	6,968,284,047	11.1	12.5
Container	5,000–7,999 TEU	40,355	70%	25.3	4,233,489,679	15.2	16.6
Container	3,000–4,999 TEU	28,784	70%	23.3	2,820,323,533	15.2	16.6
Container	2,000–2,999 TEU	16,800	70%	20.9	1,480,205,694	18.3	20.0
Container	1,000–1,999 TEU	7,000	70%	19.0	578,339,367	29.4	32.1
Container	0–999 TEU	3,500	70%	17.0	179,809,363	33.3	36.3
Vehicle	4,000+ ceu	7,908	70%	19.4	732,581,677	25.2	32.0
Vehicle	0–3,999 ceu	2,808	70%	17.7	226,545,399	47.2	57.6
Ro-Ro	2,000+ lm	5,154	70%	19.4	368,202,021	45.3	49.5
Ro-Ro	0–1,999 lm	1,432	70%	13.2	57,201,146	55.2	60.3

Note: "Loaded efficiency" is the theoretical maximum efficiency when the ship is fully loaded at service speed/85% load. Since engine load at the fully loaded condition is higher than the average including ballast and other voyages, the difference between the columns "loaded efficiency" and "total efficiency" cannot be explained by differences in utilization only.

Table 9.2 *Figures of CO_2 efficiency for road freight*

	CO_2(g/tonne-km)	Method	Source
Heavy goods vehicles	138	Output-based measures combining data from “National Road Traffic Survey” and “Continuing Survey of Road Goods Transport”.	[3]
Road freight	127	Top-down approach. Trend Database. Data from Eurostat. Data only from EU region.	[3]
Trucks > 40 tonnes	80	Sample survey, 109 vehicles.	[1]
Trucks < 40 tonnes	181	Sample survey, 44 vehicles.	[1]
Road freight	153	Top-down approach. Data from *National Transportation Statistics 2007*; U.S. Department of Transportation, Research and Innovation Technology Administration: Washington, DC, 2007; and Energy Information Administration Annual Energy Outlook 2007 with Projections to 2030, Supplemental Transportation Tables	Authors’ calculation
Road freight	156	Top-down calculation based on EU statistics.	[4]
Road freight, 2007	144*	Top-down calculation based on National Japanese statistics.	[5]

* The 2007 truck transport efficiency in Japan of 144 g/kW·h is significantly better than the 2004 value, which was 174 g/kW·h. This improvement of 20% is attributed in part to the implementation of speed limits for all Japanese trucks, following a major road accident.

CO_2 efficiency of rail freight

9.9 Unlike road and sea, electricity is an important source of energy for rail transport. When assessing the CO_2 efficiency of electric trains, consideration must be given to the CO_2 that is emitted from the production of the electricity. The transport efficiency of rails depends on the speed, weight and length of the train as well as the terrain, type of cargo, height restrictions, availability of return cargo and the efficiency in the logistics of handling empty cars. Efficiency data are presented in Table 9.3. The effect of cargo type is quite important; bulk cargoes are shown to be significantly more efficient to transport than typical intermodal cargo, such as containers. Also, when taking into account electricity production from

Table 9.3 *Figures for CO_2 efficiency of rail freight*

	g of CO_2/tonne-km	Method	Source
Diesel locomotives	49	UK National Atmospheric Emissions Inventory data (1990–2004)	[3]
Rail freight	119	Top-down approach. Data from Eurostat. Data only from EU region.	[3]
Rail freight (EU average)	81	Top-down approach. Data from Eurostat.	[4]
Rail freight (US national average)	14	Top-down approach. Data from *National Transportation Statistics 2007*; U.S. Department of Transportation, Research and Innovation Technology Administration: Washington, DC, 2007; and Energy Information Administration Annual Energy Outlook 2007 with Projections to 2030, Supplemental Transportation Tables.	Authors’ calculation
Bulk cargo trains	10–14	Calculated from typical US train sizing of bulk trains 0.6–0.8 hp/short ton (0.49–0.65 kW/metric ton)	Authors’ calculation
Intermodal (container) train	35–50	Calculated from typical US train sizing of bulk trains 3–4 hp/short ton (2.2–2.9 kW/metric ton)	Authors’ calculation

coal-fuelled power plants (CO_2 marginal power) and electric transmission losses in the grid, electric trains are only marginally more energy-efficient than diesel-fuelled trains.

9.10 From these figures, it is concluded that the efficiency of rail freight ranges from 10 to 119 grams of CO_2/tonne-km, with a typical value around 48. Bulk cargo trains cover the lower end, while intermodal trains are in the high range. Naturally, the range of individual trains is wider.

Air freight

9.11 Air freight is fast but expensive, and is limited to special types of cargo where speed is essential, such as perishable goods, mail, critical spare parts, etc. Air freight is carried in dedicated freight planes but, to a certain extent, also on passenger-carrying planes. Due to fuel burn for take-off and climb, efficiency will improve with longer flights; however, at extended range, the weight of the fuel will contribute to reduced efficiency since the drag on the aircraft increases with weight. At long range, the weight of fuel may limit the maximum weight of the cargo. Efficiency figures for two widely used freight planes are shown in Table 9.4. Differences between these two planes indicate differences in engine technology and aircraft size.

Table 9.4 *Figures for CO_2 efficiency of air freight*

	g of CO_2/tonne-km	Method	Source
Boeing 747 F	435–474	Direct calculation on case study: Total capacity 113 tonnes, average utilization 70%, 453–493 kJ/km, depending on distance.	[8]
Ilyushin IL 76T	1,100–1,800	Direct calculation on case study: Cargo capacity 28–50 tonnes (depending on range), average utilization 70%, range 500–5,500 km.	Author's calculation, data from [9]

Comparison of modes

9.12 The efficiency of ships is compared with that of other modes in Figure 9.2. This figure illustrates that gains in CO_2 efficiency can be achieved by increased multimodal transport. When considering figures of this kind, the effect of cargo type should be borne in mind. Heavy (bulk) cargoes such as steel, coal, and oil can be more efficiently transported than lighter cargos (e.g., manufactured goods) on board ships, on rail and on the road; hence the potential for energy-efficient transport is much dependent on the type of goods. Figure 9.3 shows the same comparison but also includes air freight.

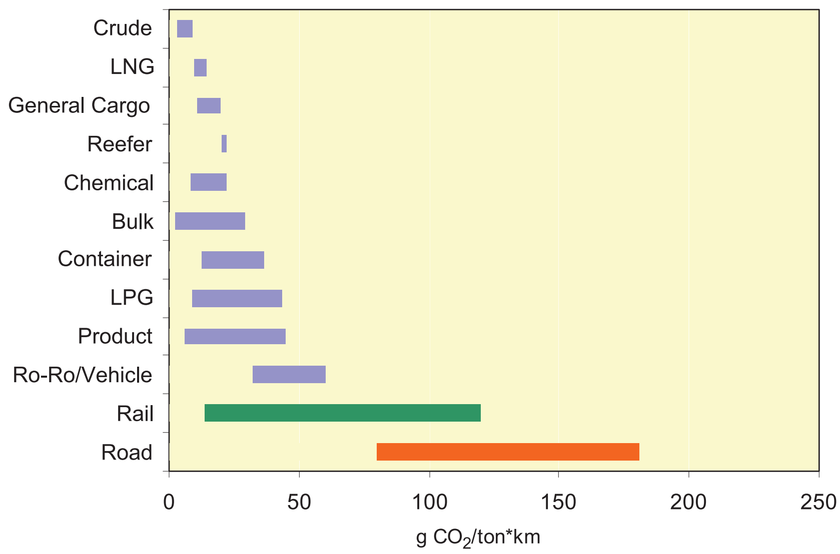


Figure 9.2 *Typical range of ship CO_2 efficiencies compared to rail and road*

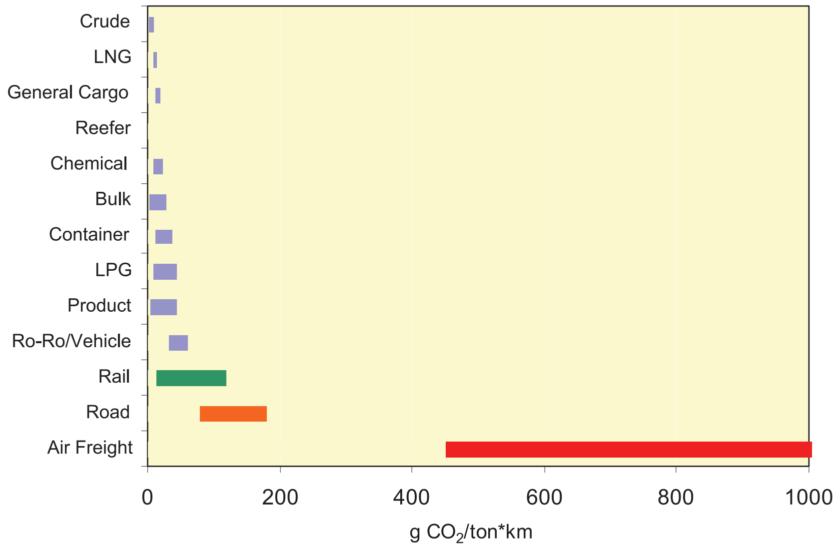


Figure 9.3 *Typical range of ship CO_2 efficiencies compared to rail, road and air freight*

HISTORIC EFFICIENCY FIGURES FOR SHIPPING

9.13 Technological improvements and increasing ship sizes have increased the efficiency of seaborne transport over time. In order to investigate historic trends in the efficiency of ships, data from Lloyd's Register – Fairplay were analysed. For this purpose, a fuel efficiency index was developed, based on deadweight, speed and fuel consumption data in the database. The efficiency values are calculated on an assumption that the average transport load is 50% of deadweight for all ships and all ages. The index is defined as follows:

$$\text{Efficiency index} = \frac{\text{Fuel consumption} \times 3.09}{0.5 \times \text{dwt} \times v}$$

where fuel consumption is given in g/h and vessel speed v is given in knots.

9.14 The efficiency values have been calculated to identify trends, and are not directly comparable to the figures given in Table 9.1 above. It should be noted that the fuel consumption figures in the database generally refer to fuel consumption for vessel charter, and include auxiliary fuel consumption and also a certain safety margin.

9.15 When analysing the fleet statistics for trends in fuel consumption values, an attempt was made to disaggregate the effects of technology, speed and vessel size. In general, this did not reveal any insights, as trends were generally very difficult to identify. The lack of precision in the data for fuel consumption may be an important reason. However, the statistics did show a clear trend in the overall best efficiency of the fleet, which combines scale, speed and technology effects.

TOTAL EMISSIONS BY TRANSPORT MODE

9.16 The total of CO_2 emissions from ships is compared to emissions from other transport modes, based on fuel consumption data reported for other sectors in IEA statistics [7]. Although some of the problems with global statistics that are discussed in Appendix 1 apply to fuel consumption statistics for all modes, the problems associated with classifying domestic versus international voyages and possible offshore bunkering are specific to shipping and aviation (see Figure 9.4 and Figure 9.5).

9.17 The use of aviation fuel is classified similarly to statistics for marine bunker fuels, although the nature of air travel is such that aircraft make fewer flights between refuelling, to manage power, weight,

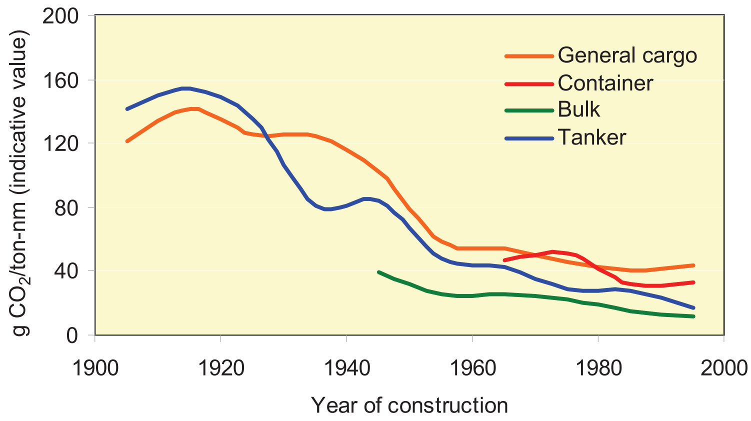


Figure 9.4 *Indicative development in average ship design transport efficiency*

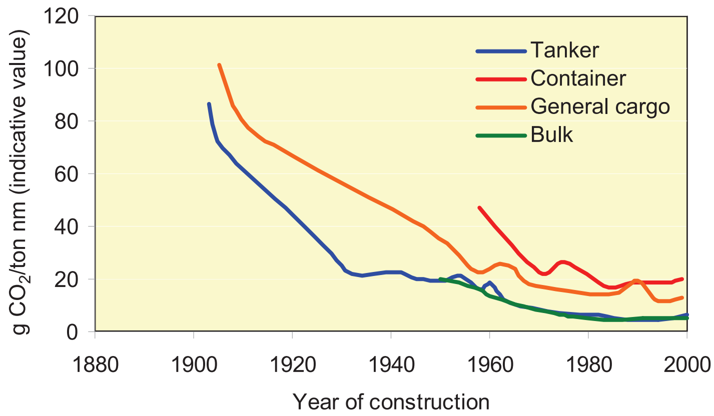


Figure 9.5 *Indicative development in maximum ship design transport efficiency*

and lift requirements. If ships were to fuel before every voyage, the IEA fuel statistics for marine would be more accurate; however, ships fuel at major bunkering market locations for multi-port voyages over weeks.

9.18 Domestic-only statistics for road and rail, aggregated by the IEA, are gathered without the conflict of classification between international and domestic activity and fuel sales recorded in compliance with IEA policy. Moreover, the volume of fuel that is used on road transport is significantly larger than the quantity of fuel used by ships. Together, this suggests that statistical confidence in the fuel data that have been collected by the IEA from reporting nations may be better for road and rail than for marine modes. Where domestic fuel sales are taxed while international marine fuels are not, the requirements to accuracy and revision of domestic fuel sales would be increased compared to international marine fuels. In the case of aviation, fuel consumption is closely monitored, since weight of fuel and aircraft range is important for the planning and approval of flights.

9.19 Since global IEA data are only available up to 2005, values for the emissions from ships in 2005 are used. This results in the figures given in Table 9.5 and in Figures 9.6 and 9.7. "Road diesel" is the total amount of diesel sold for road use, and includes the fuel that was used for cargo freight, passenger transport and diesel cars.

Table 9.5 *Emissions of CO_2 from transport modes (million tonnes, 2005)*

Rail (IEA)	Road diesel (IEA)	Aviation (IEA)	International shipping	Domestic shipping/fishing
133	4757	735	774	157

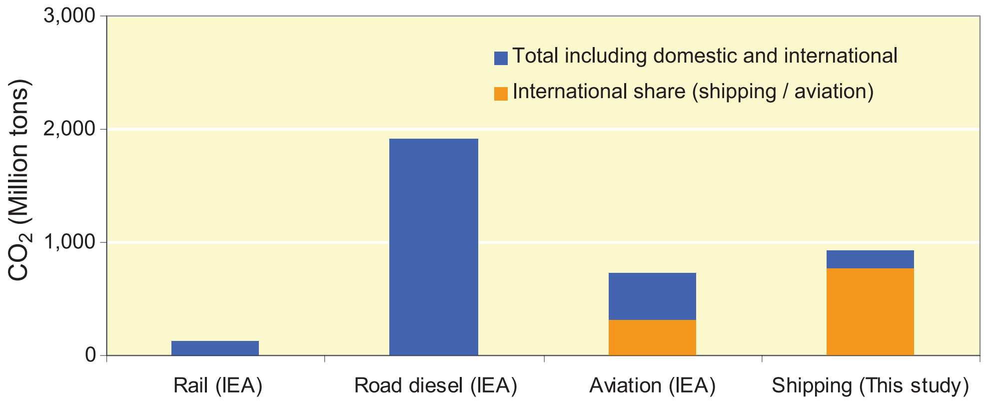


Figure 9.6 *Emissions of CO_2 in 2005 from shipping compared to other transport modes*

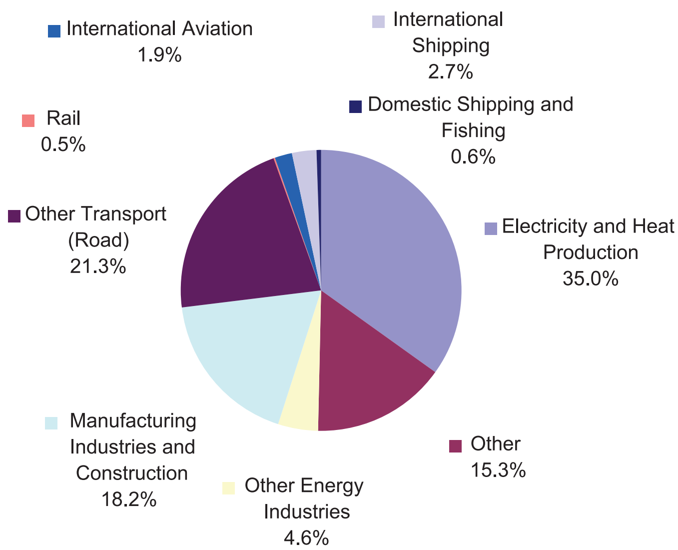


Figure 9.7 *Emissions of CO_2 from shipping compared with global total emissions*

REFERENCES

1 Review of Maritime Transport 2007, United Nations Conference on Trade and Development UNCTAD/RMT/2007 ISBN 978-92-1-112725-6. UNCTAD 2007.
2 Leonardi, J. and Baungartner, M. 2004. Transportation Research Part D. 9, 451–464
3 McKinnon, A. "CO_2 Emissions from Freight Transport in the UK", http://www.cfit.gov.uk/docs/2007/climate-change/pdf/2007climatechange-freight.pdf
4 Lindstad, H. 2008. Methodology, indicators and tools to increase European competitiveness and sustainability, 4th International Congress on Transport Research in Greece, 2008.
5 Information and research department policy Bureau, Ministry of Land, Infrastructure, Transport and Tourism, Japan; The survey on transport energy 2007.
6 Lloyds Register – Fairplay Database.
7 IEA Data Services, 2007 Energy Balances and Energy Statistics for OECD and non-OECD Countries.
8 den Boer, L.C., Brouwer, F.P.E. and van Essen, H.P. 2008. "STREAM: Studie naar TRansport Emissies van Alle Modaliteiten". CE Delft Publication 08.4482.11, March 2008.
9 Technical data on IL-76 from operator: http://www.skylineaviation.co.uk/data/il76.html

Appendix 1

Estimate of fuel consumption in 2007 by international shipping

INTRODUCTION

A1.1 In this appendix, fuel consumption by ships is estimated for the year 2007 by two methodologies:

1. based on activity data; and
2. based on fuel statistics.

A1.2 Results are compared and discussed to identify a consensus estimate for 2007 fuel consumption by international shipping and by shipping as a whole. Estimates of fuel consumption by ships are based on activity data.

METHODOLOGY

A1.3 The estimation of fuel consumption entails a significant degree of uncertainty, as evidenced by the differences that have been observed in previous estimates (Corbett *et al.*, 1997 [15]; Corbett and Köhler, 2003 [1]; Endresen *et al.*, 2003, 2007 [5, 6]; Eyring *et al.*, 2005a [3]; Olivier *et al.*, 2001 [11]; Skjølsvik *et al.*, 2000 [12]; Gunner, 2007 [8]).

A1.4 Fuel consumption for the world fleet is estimated in an "activity-based bottom-up" approach where the fuel consumption is estimated for individual categories of ships. The estimates of fuel consumption are then added together to find the global total. Ship categories for use in this inventory have been chosen so that they represent distinct ship types in terms of not only size but also typical operational patterns, which is beneficial to identify and assess activity data.

A1.5 The Main Engine (ME) fuel consumption of a ship category is estimated by multiplying the number of ships in each category with the average ME power to find the installed power (kW) by category. The annual power outtake (kW·h) is then estimated by multiplying the installed power with a category-specific estimate of the operating hours of the main engine and the average engine load factor. Finally, the total fuel consumption is estimated by multiplying the power outtake with the specific value of consumption of fuel oil that is applicable to the engines of the given category (g/kW·h). The process of estimating the fuel consumption of a ship category is illustrated in Figure A1.1. The same principle is applied to estimate the fuel consumption of the auxiliary engine.

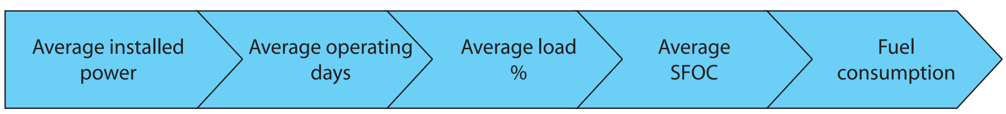


Figure A1.1 *Calculation of fuel consumption*

EMISSION INVENTORY MODEL INPUT DATA

A1.6 The emission inventory requires data for each ship category on:

– number of ships;
– average power (kW) of main and auxiliary engines;

- average age (years) of main engines (this is used to improve the estimates of fuel consumption);
- average design speed (knots) of ships (this is used when processing AIS data and estimating load);
- average specific consumption (g/kW·h) of fuel oil by the main and auxiliary engines;
- average running hours (days) for the main and auxiliary engines;
- average load (% MCR) on main and auxiliary engines;
- average consumption (tonnes/year) of fuel by the steam boiler;
- average consumption (tonnes/year) of fuel in the boiler; and
- average carbon content (grams of carbon per gram of fuel) of the fuel.

SHIP COUNT AND TECHNICAL DATA

A1.7 Statistical information on the world fleet was obtained from the Lloyd's Register – Fairplay database for the year 2007. This database contains information on all ships larger than 100 GT. An extended version of the Lloyd's Register – Fairplay database which contains additional technical information, such as power of the auxiliary engine and the vessel's design speed, was used [16]. There may be some missing raw data in the extended Lloyd's Register – Fairplay database concerning certain specific technical data. Therefore, for these special fields and for specific uses, Lloyd's Register – Fairplay has a version of the database where fields have been populated with estimated values, which were obtained by using statistical relationships. This means that the precision of additional data (such as vessel's design speed and power of the auxiliary engine) may be lower than that of the core data (such as ship numbers, tonnage and power of the main engine). The key data that have been used in this report are shown in Table A1.8.

AVERAGE SPECIFIC CONSUMPTION OF FUEL OIL BY THE MAIN AND AUXILIARY ENGINES

A1.8 Specific fuel oil consumption (SFOC) denotes fuel consumption in relation to work done, and is commonly expressed in g/kW·h. The specific fuel oil consumption depends on a range of parameters, including engine size, age and the energy density of the fuel. Data on fuel consumption can be obtained from test-bed results, from measurements taken during sea trials and they may also, to a certain extent, be deduced from figures of daily fuel consumption given in charter contracts and listed in ship databases. SFOC may also be calculated based on thermodynamic first principles and the characteristics of the engine. Typical values of specific fuel oil consumption (SFOC) are given in Table A1.1. These figures have been established by reviewing various CIMAC papers [25], manufacturer's catalogues and *Diesel & Gas Turbine Worldwide* [18]. The figures indicate a difference of about 10% depending on age category and 20% depending on size.

Table A1.1 *Typical values of specific fuel oil consumption (g/kW·h) [17]*

Engine year of build	2-stroke low-speed	4-stroke medium-/high-speed (> 5000 kW)	4-stroke medium-/high-speed (1000–5000 kW)	4-stroke medium-/high-speed (< 1000 kW)
1970–1983	180–200	190–210	200–230	210–250
1984–2000	170–180	180–195	180–200	200–240
2001–2007	165–175	175–185	180–200	190–230

A1.9 Specific fuel oil consumption data are measured in an engine test-bed, except for very large (two-stroke) engines that are simply too large to fit in a test-bed. The fuel consumption is determined and given in accordance with standard ISO procedure and reference conditions (ISO 3046–1) and corrected to standard fuel energy and standard ambient conditions. The best value of specific fuel oil consumption corresponds to a single operating point.

A1.10 The fuel consumption in actual operation is expected to be higher than when measured in test-bed conditions. The reasons for this include:

- the engine is not always operating optimally at its best operating point;
- the energy content of the fuel may be lower than that of the test-bed fuel (for engines using residual fuels, this typically amounts to about 5%);
- best SFOC values are given with 5% tolerance; and
- engine wear, ageing and maintenance (wear of fuel injectors and injection pumps, improper settings, fouling of the turbocharger, increased resistance of oil filters, fouling of the heat exchanger and more).

A1.11 Considering the differences between the SFOC of new and old engines and the differences in average age of engines, the values in Table A1.2 have been used in the inventory model. Further refinements, such as differentiation by power/cylinder or distinction of slow- and medium-speed engines, could not be done since the ship database does not contain data on the number of engine cylinders or the stroke number.

Table A1.2 *Values of specific fuel oil consumption (g/kW·h) of main engines that have been used in the inventory model*

Engine age	Above 15,000 kW	15,000–5,000 kW	Below 5,000 kW
before 1983	205	215	225
1984–2000	185	195	205
2001–2007	175	185	195

A1.12 Steam turbines that are used in Liquefied Natural Gas (LNG) tankers are assumed to consume 275 g/kW·h on a heavy fuel oil (HFO) basis. This figure has been derived by considering the fuel consumption figures for a turbine-driven LNG ship in operation. When considering the SFOC of auxiliary engines, consideration was given to the fact that auxiliary engines are expected to operate extensively on part load. The values that were used in the model are given in Table A1.3.

Table A1.3 *Values of specific fuel consumption (g/kW·h) of auxiliary engines that have been used in the inventory model*

Engine age	Above 800 kW	Below 800 kW
Any	220	230

INPUT DATA FOR ACTIVITY

A1.13 The emission model requires certain inputs which describe the activity of the ships. These are:

- average running hours for the main and auxiliary engines;
- average load on main and auxiliary engines; and
- average fuel consumption of the steam boiler.

A1.14 Estimation of activity is particularly challenging because activities vary to a certain degree from one year to the next, depending on factors such as demand for transport capacity in relation to the size of the fleet in any given segment. Previous research has estimated activity from the service record of engine running hours, by interviews, using Lloyd's Marine Intelligence Unit, data on ship movement and more. For this study, data from Automatic Identification Systems (AIS) from the AISLive network were used as a new and independent source of information about activity.

AIS DATA

A1.15 An Automatic Identification System (AIS) is a safety device that automatically transmits information – including the ship's identity and its type, position, course, speed, navigational status (e.g., "at anchor" or "moving with engines running") and other safety-related information – to appropriately equipped shore stations, other ships and aircraft.

A1.16 The International Convention for the Safety of Life at Sea, 1974 (SOLAS) [28] requires an AIS transponder to be fitted aboard all ships of 300 gross tonnage (GT) and upwards engaged on international voyages, cargo ships of 500 gross tonnage and upwards not engaged on international voyages and all passenger ships irrespective of size. The requirement became effective for all ships as of 31 December 2004. Ships fitted with AIS are to maintain AIS in operation at all times, except where international agreements, rules or standards provide for the protection of navigational information.

A1.17 AISLive is a network of shore-based AIS receivers covering more than 2000 locations in 100 countries. This network collects and processes AIS data and makes the information available for various analytical purposes, on a commercial basis. For this project, a database containing all AIS observations logged each hour for the year 2007 was used. The location of these receivers is indicated in Figure A1.2. In this figure, green squares signal the position of AIS base stations in the network. Orange and yellow and red squares signal that there is a higher density of receivers.

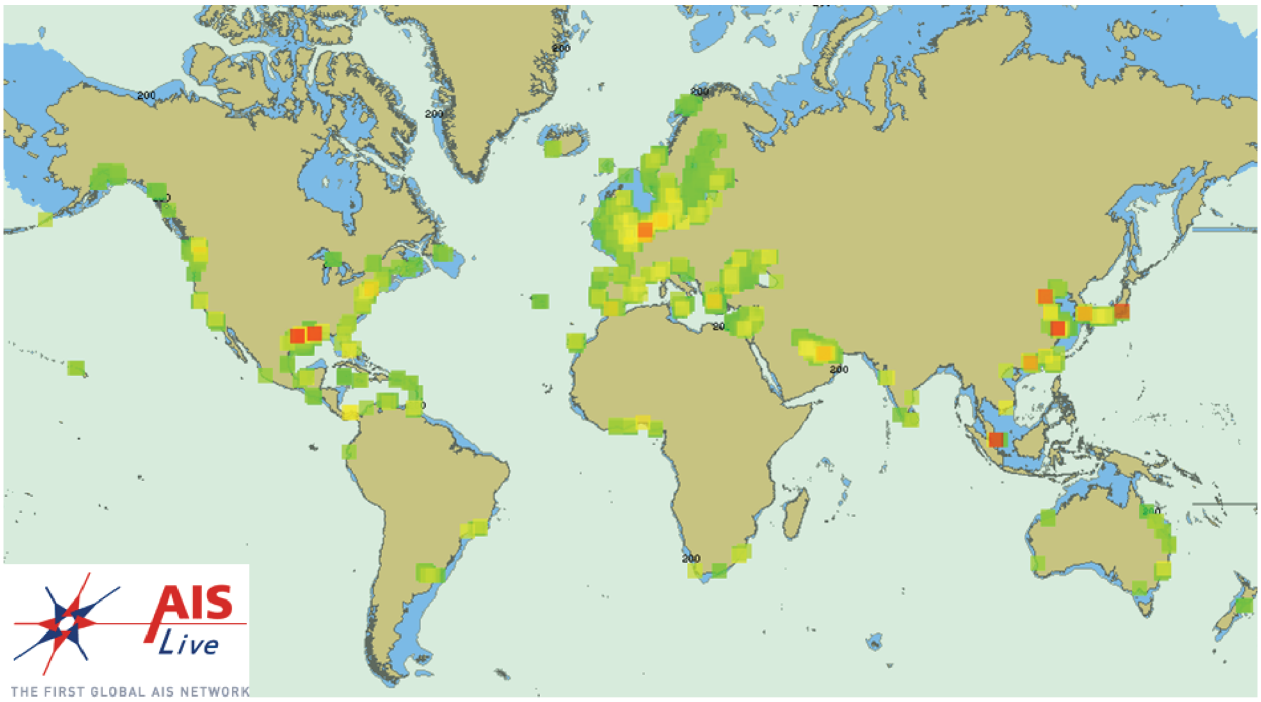


Figure A1.2 *Shore-based receivers in the AISLive network (Lloyd's Register – Fairplay)*

A1.18 AIS shore stations are able to continuously detect the presence of ships in the vicinity of the shore station. Ship movement and speed are also detected; however, the range is limited (typically to somewhere around 100 km, depending on the height of antenna, atmospheric conditions, and more). Therefore, the AIS network cannot track ships between ports. However, since the identity of a ship is broadcasted, it is possible to record the time between when a ship disappears from the area of coverage of one port within the AIS network and appears in another. Assuming that the ship travels directly between these ports, these data would provide the time at sea and the average speed. Unfortunately, it is not possible to determine if the ship has detoured and/or called into other ports that are not part of the AIS network.

A1.19 Data from the AIS network were prepared by counting, for the year 2007, the number of hours that each ship that was detected by the network spent either:

– within the area of coverage of the AIS network, status: "in port";
– within the area of coverage of the AIS network, not in port, status "at anchor";
– within the area of coverage of the AIS network, moving; and
– outside the area of coverage of the AIS network.

Whenever a ship left an area of coverage of the AIS network, the time until it reappeared in another area was used to calculate its average speed, assuming that the ship had followed the shortest route between the observations. This calculation does not take into account the presence of land masses, which could cause significant error in the estimation of certain distances. However, since ships will be detected not only by the ports of departure and arrival but also when passing other ports as well as other strategic waypoints that are covered by the AIS network (e.g., Suez, Panama, Gibraltar, Strait of Malacca, Alaska Peninsula, south of Sri Lanka), the error of making this assumption of a direct route will be reduced.

A1.20 Voyages where the calculated average speed is above 80% of the service speed for the particular ship (as given in the extended Fairplay database) were categorized as "normal" while voyages where the average speed is less than 80% were categorized as "slow". By this procedure, the ship activity could be grouped into four categories; see Table A1.4.

Table A1.4 *Definition of data categories*

Category	Description
Port	Hours within range of the AIS network, with navigation status "moored"
Anchor	Hours within range of the AIS network, with navigation status "at anchor"
Slow	Hours within and outside the AIS network, calculated average speed < 80% of service speed.
Normal	Hours within and outside the AIS network, calculated average speed > 80% of service speed.

A1.21 The input summary table (Table A1.5) shows the number of vessels (unique counts) that were detected by the global AISLive network in 2007. The table also shows the number of ships in the database in April 2008 and the percentage of the ships in the database that have been observed at least once within the AIS network. In general, the indicated coverage is high for large cargo-carrying ships; however, for smaller ships (and particularly fishing vessels), the coverage is low. This is believed to be a result of smaller ships calling more frequently at smaller ports and operating in areas which are less likely to be part of the AISLive network.

Table A1.5 *(Specimen AIS data (accumulated hours, by ship category)*

Type	Size	Port (h)	Anchor (h)	Slow (h)	Normal (h)	Total (h)
Bulker	100,000–199,999 dwt	225,065	348,160	728,101	2,860,034	4,161,360

Type	Size	Service speed (knot)	Cut-off speed "slow" (knot)	Average speed "slow" (knot)	Average speed "normal" (knot)
Bulker	100,000–199,999 dwt	14.1	11.3	7.6	12.8

A1.22 In some instances, more vessels are detected by the AIS system than are recorded in the statistics. This may be caused by a reduction in fleet size or by a delay in the updating of the statistics or other errors.

ESTIMATES OF DAYS AT SEA AND AVERAGE POWER

A1.23 The inventory model requires an estimate of the average number of days ships within each category spend moving at sea. In order to use the AIS data to estimate days at sea, it is first necessary to interpret the data. An example of the AIS data is shown in Table A1.5.

A1.24 Hours spent in port and at anchor are not spent at sea. Time allocated in the "slow" category is likely to include both some time moving but also some time in port to justify a detour, which could explain the unusually low average speed. Another reason for slow voyages would be detouring around land that is not anticipated in the calculation of distance from AIS data. Time in the "normal" category could, in theory, contain some port time and detouring also; however, the difference between average observed speed and service speed could also be caused by temporary speed reductions in congested waters, detours caused by weather and other natural causes. For the purpose of this study, it was assumed that hours recorded in the "normal" speed category are all at sea. What remains is interpreting the hours that have been logged by the Lloyd's AIS analysis as "slow".

A1.25 If it is assumed that "slow" voyages are a result of stops in ports that are on the route between the two ports where AIS is used, and also assuming that the speed at sea is the same as the average speed that has been observed in "normal" voyages, then the time at sea can be calculated as:

$$\text{Total time at sea} = \text{Time}_{\text{normal}} + \text{Time}_{\text{slow}} \times \frac{\text{Average speed}_{\text{slow}}}{\text{Average speed}_{\text{normal}}}$$

The assumption that additional ports are on a route is not unreasonable, since a significant share of shipping follows coastlines where stops could be possible without making a significant detour. However, if ships do detour significantly and the additional ports are not generally on the route between them, the above calculation would be in error and would under-estimate time at sea. Naturally, the accuracy of the estimate of time at sea depends not only on the validity of the assumptions but also on how representative the data are for the ship category as a whole.

A1.26 The AIS data can also be used to estimate average engine load. This is done by comparing the average speed that is observed at sea with vessel service speed, while assuming a third-power relationship between power and speed and a sea margin of 10% for all vessels (as illustrated in Table A1.6). This table shows that, with a 10% service margin,[1] the maximum speed that can be obtained with a clean hull and in calm weather at full design draught (i.e. 100% speed) corresponds to 90% MCR. When the speed is reduced, the propeller load and the engine load are reduced correspondingly. The average load can then be indicated by comparing the speed that is observed by AIS with the maximum speed of the ship. This estimate will only be indicative, since it does not include a number of significant parameters (including the effect on average load of variations of speed *en route*, wind, waves, hull degradation or the draught of the ship.

Table A1.6 *Typical engine and propeller loads corresponding to ship speed in clean-hull calm-sea conditions at the design draught*

Ship speed	50%	75%	80%	90%	95%	100%
Propeller load (% kW)	13%	42%	51%	73%	86%	100%
Engine MCR (% MCR)	11%	38%	46%	66%	77%	90%

A1.27 Following the above approach, AIS data and fleet statistics were used to estimate days at sea and the main engine load for all ship categories in the inventory. The resulting estimates of days at sea were subsequently reviewed in the light of other data, such as activity data from previous studies, and logistic analysis. Thereafter, the average main engine load was assessed by considering other data sources and the effects of ballast and low-load runs which would not be accurately predicted using this methodology. Several changes were made both with regard to days at sea and load. In particular, changes were made to all categories of small ships where AIS coverage is low and where the estimate of number of days at sea from AIS data was significantly higher than could be expected from other data. The resultant input data are shown in Table A1.8.

AVERAGE LOAD AND OPERATING HOURS OF THE AUXILIARY ENGINE

A1.28 The average load and the operating hours of the auxiliary engine are needed to calculate the fuel consumption of the auxiliary engine. The load and the operating hours vary greatly between ship types. Typically, and according to Lloyd's data, ships will normally have at least three generators; one is operational, one is on standby and the third is available for maintenance. Normally, generators will be operated

1 A service margin is used to prevent engine overloading in the event of extreme fouling of the hull and/or extreme weather.

Table A1.7 *Comparison of activity-based inventories of bunker fuel (comparison of results: see Table A1.19)*

	Primary source of activity data	Ship category: average main engine operating hours (days/year)	Average main engine SFOC (g/kW·h)	Average main engine % MCR
Corbett *et al.*, 2003 [1]	Engine running hours and operating data provided by a major manufacturer of diesel engines	Cargo ships: 229–292 (average 271)	Cargo ships: average 206 (range 185–225)	Cargo ships: 65–70% average load, based on rated power. 55–80% max. All types: weighted average 63%
Eyring *et al.*, 2005 [3]	Engine running hours and operating data provided by a major diesel engine manufacturer	Cargo ships: 225–275	Cargo ships: average 210	Cargo ships: average 70–80%
IMO expert group, 2007 [4]	Questionnaires to 20 selected major shipowners	All types: 175–310 (weighted average 226)	All types: weighted average 185	All types: 62–90% (weighted average 80%)
Endresen *et al.*, 2007 [5]	Published data on seaborne trade length of haul, laid up tonnage, cargo capacity utilization and operational speed	Cargo ships: average 181	Cargo ships: average 221	Cargo ships average 70%
This study, consensus estimate	AIS data combined with fleet statistics and results from previous work. Contributors to studies listed above have been represented in the team behind this update.	All types: 100–285 (weighted average 240)	Weighted average all ship types 196	Cargo ships: 65–80% (weighted average 70) All types: 16–80% (weighted average 64%)

on a rota basis to distribute their running hours. The standby generator(s) will be used in periods with high load or when there is high risk of high load peaks, such as when thrusters are used for manoeuvring or when large pumps, winches or cranes will be operated. This typically occurs at arrival in port. Certain ships will also need electricity for purposes of caring for the cargo, such as ventilation and refrigeration. Other ships may use a shaft generator. In this case, auxiliary engines would not normally be operated at sea. Following this discussion, the research team made assumptions for annual running hours of the auxiliary engine and its load factors. In doing this, the relative consumption between main and auxiliary engines was considered and compared with typical operating data for certain ship categories.

AVERAGE FUEL CONSUMPTION OF THE STEAM BOILER

A1.29 All ships that use residual fuel oil will need to heat this fuel to maintain it as a liquid. When the ship is at sea, this heat will normally be taken from the exhaust waste by way of a steam boiler; hence no additional fuel is consumed. In port, however, the main engine is not running, and the ship may therefore need to generate steam by using an auxiliary oil-fuelled boiler. In the total picture, the amount of fuel that is used to heat fuel is considered to be insignificant. For tankers, where steam is required for cargo heating and/or pumping work, the consumption of fuel by the steam boiler is no longer insignificant. For these ships, the consumption of fuel oil by the boiler is estimated on the basis of the work of the IMO Expert group (BLG 12/INF.10) [4].

1. **VLCC tankers**

   It is assumed that Very Large Crude Carrier (VLCC, dwt 200,000+) oil tankers undertake 10 voyages per annum, of which five are loaded; thus five discharges are made each year. For each discharge, a VLCC (dwt 200,000+) uses 250 tonnes of fuel oil to power the main cargo pumps.

Table A1.8 *Summary table – input data that have been used in the inventory*

Category	Size / type	No. of ships (2007)	Ave. GT	Ave. ME kW	Ave. per engine Aux kW	AIS unique counts (4)	AIS coverage (5)	Days at sea (1) Modelled	Avg. ME load Modelled	Avg. AUX running days (2)	Avg. AUX load Modelled	Fuel type (3)
Crude oil tanker	200,000+ dwt	494	155,685	24,610	1,034	514	99%	274	73%	450	50%	HFO
Crude oil tanker	120,000–199,999 dwt	353	80,711	17,075	1,232	368	100%	271	80%	450	50%	HFO
Crude oil tanker	80,000–119,999 dwt	651	56,921	12,726	769	685	101%	254	80%	450	50%	HFO
Crude oil tanker	60,000–79,999 dwt	180	39,498	10,529	731	190	101%	238	70%	400	50%	HFO
Crude oil tanker	10,000–59,999 dwt	245	24,290	7,889	729	229	91%	238	70%	400	50%	HFO
Crude oil tanker	0–9,999 dwt	114	2,085	1,865	222	49	41%	180	65%	400	50%	MDO/HFO
Products tanker	60,000+ dwt	198	46,775	12,644	780	215	99%	171	80%	450	50%	HFO
Products tanker	20,000–59,999 dwt	456	24,262	8,482	736	455	96%	171	66%	450	50%	HFO
Products tanker	10,000–19,999 dwt	193	9,723	4,640	535	147	75%	183	70%	400	50%	HFO
Products tanker	5,000–9,999 dwt	466	4,264	2,691	291	306	63%	177	75%	400	50%	MDO/HFO
Products tanker	0–4,999 dwt	3,959	1,056	1,032	123	909	23%	175	65%	400	50%	MDO/HFO
Chemical tanker	20,000+ dwt	1,010	24,917	9,027	837	1,059	100%	251	80%	450	50%	HFO
Chemical tanker	10,000–19,999 dwt	584	9,357	5,161	623	621	95%	246	80%	400	50%	HFO
Chemical tanker	5,000–9999 dwt	642	4,651	3,252	416	615	92%	246	76%	400	50%	MDO/HFO
Chemical tanker	0–4,999 dwt	1,659	1,331	1,257	216	668	40%	180	65%	400	50%	MDO/HFO
LPG tanker	50,000+ cbm	138	43,784	13,494	1,004	147	103%	273	70%	450	50%	HFO
LPG tanker	0–49,999 cbm	943	4,834	3,225	436	697	72%	180	65%	400	50%	MDO/HFO
LNG tanker	200,000+ cbm	4	135,846	37,322	3,210	8	100%	260	70%	450	50%	HFO
LNG tanker	0–199,999 cbm	239	90,933	24,592	2,610	251	98%	274	70%	400	50%	HFO
Other tanker	Other	402	2,030	1,522	210	163	41%	180	65%	400	50%	MDO/HFO
Bulk	200,000+ dwt	119	114,519	17,224	794	101	97%	281	71%	450	60%	HFO
Bulk	100,000–199,999 dwt	686	83,619	15,108	697	695	99%	279	70%	450	60%	HFO
Bulk	60,000–99,999 dwt	1,513	39,568	9,912	549	1,509	98%	271	70%	450	60%	HFO
Bulk	35,000–59,999 dwt	1,864	27,596	8,209	533	1,859	96%	262	70%	425	60%	HFO
Bulk	10,000–34,999 dwt	2,090	15,351	6,436	458	1915	90%	258	70%	400	70%	HFO
Bulk	0–9,999 dwt	1,120	1,942	1,532	237	382	34%	180	65%	400	60%	MDO/HFO
General cargo	10,000+ dwt	674	11,382	5,914	414	491	71%	260	80%	410	60%	HFO
General cargo	5,000–9,999 dwt	1,528	4,704	2,939	235	1,171	76%	272	80%	410	60%	MDO/HFO
General cargo	0–4,999 dwt	11,006	1,061	868	90	3,553	32%	180	65%	380	50%	MDO/HFO
General cargo	10,000+ dwt, 100+ TEU	1,225	15,641	7,882	628	1,160	94%	240	65%	410	50%	HFO

General cargo	5,000–9,999 dwt, 100+ TEU	1,089	5,294	3,720	401	969	88%	180	65%	380	50%	MDO/HFO
General cargo	0–4,999 dwt, 100+ TEU	1,486	2,724	1,860	249	1,321	88%	180	65%	380	70%	MDO/HFO
Other dry	Reefer	1,239	4,998	4,941	551	930	75%	256	69%	360	60%	MDO/HFO
Other dry	Special	228	12,201	5,787	511	174	78%	235	65%	360	60%	MDO/HFO
Container	8,000+ TEU	118	100, 082	68,477	3,081	145	94%	241	67%	600	60%	HFO
Container	5,000–7,999 TEU	417	70,290	55,681	2,433	438	97%	247	65%	600	60%	HFO
Container	3,000–4,999 TEU	711	45,317	34,934	1,782	732	99%	250	65%	500	60%	HFO
Container	2,000–2,999 TEU	667	29,363	21,462	1,359	695	99%	251	65%	500	60%	HFO
Container	1,000–1,999 TEU	1,115	16,438	12,364	985	1,157	98%	259	65%	450	60%	HFO
Container	0–999 TEU	1,110	6,967	5,703	600	1,025	90%	180	65%	400	60%	MDO/HFO
Vehicle	4,000+ ceu	398	51,549	13,137	1,034	419	97%	284	76%	300	70%	HFO
Vehicle	0–3,999 ceu	337	20,561	7,971	671	289	86%	271	73%	300	60%	HFO
Ro-Ro	2,000+ lm	194	25,725	15,736	1,293	186	96%	219	65%	360	50%	HFO
Ro-Ro	0–1,999 lm	1,517	3,557	2,934	381	602	40%	180	65%	360	50%	MDO/HFO
Ferry	Pax Only, 25 kn +	984	302	3,113	60	244	25%	262	65%	360	60%	MDO/HFO
Ferry	Pax Only, <25 kn	2,108	392	1,213	79	215	10%	258	80%	360	60%	MDO/HFO
Ferry	RoPax, 25 kn +	177	12,119	27,395	785	125	71%	232	65%	360	70%	MDO/HFO
Ferry	RoPax, <25 kn	3,144	4,723	4,891	469	1,054	34%	254	74%	360	70%	MDO/HFO
Cruise	100,000+ gt	24	119,041	66,523	1,500	16	67%	262	65%	360	70%	HFO
Cruise	60,000–99,999 gt	69	79,541	49,779	3,269	46	67%	227	65%	360	70%	HFO
Cruise	10,000–59,999 gt	130	29,559	19,048	1,780	87	67%	227	65%	360	70%	HFO
Cruise	2,000–9,999 gt	74	4,851	4,026	702	47	64%	227	65%	360	70%	HFO
Cruise	0–1,999 gt	202	664	945	143	129	64%	180	65%	360	70%	MDO
Yacht	Yacht	1,051	560	2,285	141	467	44%	100	50%	360	70%	MDO/HFO
Offshore	Crew/supply vessel	607	246	2,546	69	187	30%	232	25%	360	60%	MDO/HFO
Offshore	Platform supply	1,733	1,127	2,527	316	956	54%	191	30%	360	60%	MDO/HFO
Offshore	Tug/supply ship	550	905	3,218	253	285	52%	205	16%	360	60%	MDO/HFO
Offshore	Anchor handling T/S	1,190	1,545	5,266	574	810	66%	210	31%	360	50%	MDO/HFO
Offshore	Support/safety	487	1,486	2,504	291	265	54%	194	34%	360	70%	MDO/HFO
Offshore	Pipe (various)	246	6,657	6,195	667	115	47%	233	16%	360	70%	MDO/HFO
Service	Research	895	1,641	2,386	367	372	41%	187	49%	360	60%	MDO/HFO
Service	Tug	12,330	281	1,903	96	2,186	18%	215	40%	360	50%	MDO/HFO
Service	Dredging	1,206	2,191	2,614	516	374	31%	175	43%	360	50%	MDO/HFO
Service	SAR & Patrol	992	523	2,597	145	171	17%	180	28%	360	70%	MDO/HFO

Page 145

Table A1.8 *Continued*

Category	Size / type	No. of ships (2007)	Ave. GT	Ave. ME kW	Ave. per engine Aux kW	AIS unique counts (4)	AIS coverage (5)	Days at sea (1) Modelled	Avg. ME load Modelled	Avg. AUX running days (2)	Avg. AUX load Modelled	Fuel type (3)
Service	Workboats	1,067	1,559	2,077	174	266	25%	161	25%	360	60%	MDO/HFO
Service	Other	813	1,360	2,613	194	201	25%	156	51%	360	60%	MDO/HFO
Misc	Fishing	12,849	313	687	164	484	4%	285	26%	360	70%	MDO/HFO
Misc	Trawlers	9,709	601	956	319	776	8%	261	58%	360	70%	MDO/HFO
Misc	Other fishing	1,291	1,296	1,388	236	322	25%	249	77%	360	70%	MDO/HFO
Misc	Other	667	11,497	9,000	647	168	25%	153	65%	360	70%	MDO/HFO

(1) "Days at sea" expresses the total accumulated time at sea. The number of days when the ship has been at sea part of the time will be higher. This distinction is primarily of interest for small vessels on short routes, ferries, etc.
(2) "Average AUX running days" is the sum of several engines, resulting in a more than 356 running days per year.
(3) "Fuel type" denotes typical fuel type for main and auxiliary engines. Multiple fuel types indicate either frequent difference between main and auxiliary engines or that a fraction of the ships in this category is expected to use either fuel type.
(4) "AIS unique counts" indicates the number of different vessels detected.
(5) "AIS coverage" denotes the ratio of ships detected at least once during the year to the number of ships in the database used.

2. **Suez Max tankers**

   It is assumed that Suez Max (120,000–200,000 dwt) crude oil tankers undertake 12 voyages per annum, of which six are loaded; thus six discharges are made each year. For each loaded voyage, a Suez Max is estimated to use 150 tonnes of boiler fuel oil to power the cargo pumps and also to heat certain cargoes.

3. **Aframax tankers**

   It is assumed that the Aframax (80,000–120,000 dwt) crude oil tankers carry heated cargo for 50 days per year. Heating the cargo requires 60 tonnes of boiler fuel oil per day.

4. **Small crude tankers**

   The smaller crude tankers (60,000–79,999 dwt, 10,000–59,999 dwt, and < 9,999 dwt) are assumed to carry heated cargoes for 100 days per year. The consumption of fuel oil by the boiler to heat the cargo is 30, 15 and 5 tonnes, respectively, per day.

5. **Product tankers**

   For product tankers, the assumptions are:

   - 40% of all product tankers carry heated cargoes;
   - these cargoes are carried for 150 days per annum; and
   - the consumption of fuel oil by the boiler is 5, 15, 30, 50 and 60 tonnes per day, respectively, for each size category in the inventory model (Table A1.8).

6. **LNG tankers**

   For consistency, and to ease future scenario modelling, the consumption of the boiler is modelled as consumption by the main engine, taking into account the lower efficiency of steam boilers and the change in the carbon fraction of the fuel to account for the fraction of LNG boil-off that is in the fuel.

CONFIDENCE AND UNCERTAINTY

A1.30 The activity-based estimate of consumption of marine bunkers is based on a series of inputs. An uncertainty is associated with each and all of these inputs. A list of these inputs and a qualitative description of the confidence of the inputs and the uncertainty in their values is given in Tables A1.9 and A1.10.

A1.31 Previous research has shown that the input variables that cause the greatest uncertainties in this type of bottom-up activity model are the estimates of engine load factor (duty cycle) and of the number of days at sea (engine running hours) [1]. The present study uses extensive global AIS data to assist the assessment of both of these inputs. Even so, the uncertainty in an inventory of this type remains significant. This is apparent when comparing key inputs that have been used in previous research. Estimates of key parameters and data sources for other estimates are given in Table A1.7. As seen in Table A1.7, various sources of data and assessments result in differences for inputs to models, which again result in different estimates. The figures that are cited are indicative of typical inputs; however, they are not fully comparable, due to differences in categorization and also in definition of inputs.

A1.32 In order to get a better grip of the uncertainties, two alternate sets of model input data were developed to generate alternative high and low estimates of fuel consumption. In doing this, only the days at sea and the average load factor were manipulated. For each category, combinations of days at sea and load which would result in respectively high and low fuel consumption were identified. These combinations were considered to be feasible, but significantly less likely than our consensus estimate. The high and low bounds that are generated are not absolute limits.

ESTIMATION OF THE CONSUMPTION OF BUNKERS BY INTERNATIONAL SHIPPING, BASED ON THE ACTIVITY-BASED MODEL

A1.33 The activity-based model that was used in this project cannot differentiate between emissions from international and from domestic shipping. In order to provide an estimate for emissions from international

Table A1.9 *Confidence and uncertainty of calculation of fuel consumption of main engines*

Input	Source	Confidence	Comments
Number of ships, by category	Fairplay database	Very high: well known	High accuracy of registered ships. Uncertainty regarding whether all ships are actively trading or if some ships in some categories are laid up, etc.
Average main engine size	Fairplay database	Very high: well known	High accuracy expected.
Average operating days of main engine	Calculated from AIS data except for ship types with low AIS coverage	Moderate, but dominates uncertainty	Accuracy depends on accuracy of the AIS collection system, how representative are the ships that are moving between ports with AIS network coverage, assumptions made for ship movement, cut-off and filtration of data, assumed average offhire/lay-up, calculations of port-to-port distance, vessel design speed.
Average load of main engine	Default values calculated from AIS average speed and Fairplay design speed. Defaults were replaced where other data or special conditions suggested this to be appropriate.	Moderate; secondary influence on uncertainty	Calculations are sensitive to data on vessel design speed from the extended Lloyd's database and errors in estimating the at-sea speed from AIS data. Also, the load will be over-estimated when the ship is in ballast or lightly loaded. Where other data suggest that the results are unreasonable, calculated values are substituted by expert judgement.
Average offhire/lay-up	Assumed	Moderate; influences the operating days of the main engine	It is assumed for all ships that the effective calendar is 355 days (on average, 10 days is spent out of active trade).
Calculations of AIS observation-to-observation distances	Calculations based on AIS coordinates	Moderate	Used for AIS calculations of average speed. Accuracy will be affected when there is a land mass within the shortest route between AIS receivers Where other data suggest that the results are unreasonable, calculated values are substituted by expert judgement.
Vessel's design speed	Extended Fairplay database	Moderate	Used to determine the cut-off between "normal" and "slow" (abnormal) voyages. Also used to estimate power factor at sea.
Average SFOC of main engine	Estimated from a wide range of test-bed and other measurement data	High; well known from operators and manufacturers	While there is some variation from engine to engine, the average figure is expected to have comparatively high accuracy.

Table A1.10 *Confidence and uncertainties of calculation of fuel consumption of auxiliary engines*

Input	Source	Confidence	Comment
Number of ships, by category	Fairplay database	Very high; well known	High accuracy of registered ships. Uncertainty regarding whether all ships are actively trading or if some ships in some categories are laid up, etc.
Average size of auxiliary engine	Extended Fairplay database	High, but with data gaps	Accuracy somewhat lower than data for the main engine; however, relatively high accuracy is expected.
Average operating days of auxiliary engine	Expert judgement and consultations with operators	Moderate; dependent upon vessel operating days and demand for the auxiliary engine	Assessment is challenging, due to variability in power demands of the ship and operating practices. While confidence is moderate, the impact on total inventory is small.
Average load of auxiliary engine	Expert judgement and consultations with operators	Moderate; dependent on vessel operating conditions and demand	Assessment is challenging, due to variability in the power demands of the ship and operating practices.
Average SFOC of auxiliary engine	Estimated from a wide range of test-bed and other measurement data	High; well known from operators and manufacturers	While there is some variation from engine to engine, the average figure is expected to have comparatively high accuracy.

Note: The confidence of the estimated fuel consumption of steam boilers must be categorized as "moderate"; however, it has little impact on the overall inventory.

Page 149

shipping by use of the activity-based model, fishing emissions must be removed from the inventory and domestic emissions (as reported in statistics for bunkers) must be subtracted from the shipping emissions.

A1.34 Using the activity-based model and the inputs as described in Table A1.8, the global emissions from all non-military shipping activities in 2007 are estimated as shown in Table A1.11.

Table A1.11 *Total fuel consumption (million tonnes) of non-military shipping (2007)*

	Low bound	Best	High bound
Total fuel consumption	279	333	400

A1.35 Low and high bounds represent feasible extremes that are considered significantly less likely than the consensus estimate. The above figure is total for all non-military shipping. Fixed offshore installations, such as production vessels and rigs, are also excluded. These figures include the fuel consumption and emissions that are already registered as arising from domestic shipping and fishing.

A1.36 Fishing emissions are unique to fishing vessels and can be subtracted from the activity-based inventory. This is done in Table A1.12.

Table A1.12 *Estimated fuel consumption (million tonnes) for total fleet during 2007, excluding fishing vessels*

	Low	Consensus	High
Total fleet inventory	279	333	400
Activity-based fishing estimate	18	21	23
Total less activity-based fishing emissions	261	312	377

A1.37 The figures for domestic fuel consumption during 2005 recorded by the IEA are shown in table A1.13, along with an estimated total fuel consumption scaled forward to 2007, using Fearnleys data for global seaborne trade as explained in paragraphs A1.50 to A1.53.

Table A1.13 *Domestic consumption figures (million tonnes) from IEA [26]*

	2005	2007 (estimated)
HFO	13.3	14.6
MDO	19.7	21.6
Total	33.1	36.2

A1.38 An estimate of the fuel consumption in 2007 for international shipping – i.e. all non-military, non-fishing consumption of fuel that is not accounted for as domestic – is then calculated, as shown in Table A1.14.

Table A1.14 *Fuel consumption (million tonnes) in 2007 by international shipping**

	Low bound	Consensus	High bound
Inventory total less fishing	261	312	377
IEA domestic shipping	36	36	36
International shipping	**225**	**276**	**340**

* Total not accounted for in statistics as domestic and fishing.

ESTIMATE OF FUEL CONSUMPTION BY SHIPS, BASED ON BUNKER FUEL STATISTICS INTRODUCTION

A1.39 The 2000 Study of GHGs from ships estimated the emissions using a fuel-based inventory approach. This approach makes an implicit assumption that world-wide sales of bunker fuel represent total consumption of fuel. The 2000 study of greenhouse gas emissions from ships reviewed different data sources for global consumption of bunkers by ships, including the IEA and the United States Energy Information Administration (EIA). A number of inconsistiencies were identified at that time.

A1.40 International sales figures of bunker fuel require summing a combination of marine fuels reported by countries under different categories (e.g., national or international bunker fuel). This can be challenging on a global scale, because most energy inventories follow accounting methodologies that are intended to conform to the International Energy Agency's energy allocation criteria [13] while some statistical sources for marine fuels do not define international marine fuels in the same way [10]. In this section we summarize the current statistical fuel data and in paragraphs A1.54 to A1.68 we present a fuel-based inventory for comparison with our more explicit activity-based inventory in paragraphs A1.3 to A1.38.

IEA STATISTICS AND REPORTING PRACTICES

A1.41 The International Energy Agency (IEA) maintains an energy database containing global records of fuel use by ships. The IEA was established by the Organization for Economic Co-operation and Development (OECD). Member Governments of the IEA are committed to taking joint measures to meet oil supply emergencies. They also have agreed to share energy information, to coordinate their energy policies and to cooperate in the development of rational energy programmes that ensure energy security, encourage economic growth and protect the environment. These provisions are embodied in the Agreement on an International Energy Programme, the treaty pursuant to which the Agency was established in 1974. The IEA database contains records of demand for (sales of) heavy fuel oil (HFO) and marine distillate fuel oil (MDO) for three categories:

1. International marine bunkers;
2. Domestic navigation; and
3. Fishing.

These terms have been defined by the IEA as follows:

1. ***International marine bunkers*** covers those 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 excluded.
2. ***Domestic navigation*** includes fuels delivered to vessels of all flags not engaged in international navigation. 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. Fuel used for ocean, coastal and inland fishing and military consumption is excluded.
3. ***Fishing*** includes fuel used for inland, coastal and deep-sea fishing. "Fishing" covers fuel delivered to ships of all flags that have refuelled in the country (including international fishing) as well as the energy that is used in the fishing industry.
4. ***Heavy fuel oil (HFO)*** defines oils that make up the distillation residue. It comprises all residual fuel oils, including those obtained by blending. Its kinematic viscosity is above 10 cSt at 80°C. The flashpoint is always above 50°C and the density is always higher than 0.90 kg/l.
5. ***Marine distillate oil (MDO)*** comprises gas oils and diesel oils sold to ships. Gas/diesel oil includes heavy gas oils. Several grades are available, depending on uses: diesel oil for diesel compression ignition (cars, trucks, marine, etc.), light heating oil for industrial and commercial uses, and other gas oil.

A1.42 In practical terms, the split between domestic and international fuel consumption means that, whenever a ship bunkers fuel, if the next port is in the same country, the complete amount of fuel is likely to be registered as "domestic". Otherwise, the fuel is likely to be recorded as "international".

ANALYSIS OF IEA STATISTICAL DATA

A1.43 The IEA maintains statistics for member and non-member countries; hence the IEA can provide global energy data. However, since non-member countries are not obliged by the IEA treaty to publish data according to their specific methodologies and standards, data that have been collected by the IEA for the non-member countries could be less accurate.

A1.44 In order to get an idea of the quality of the data of IEA bunker statistics, the data entries "International Marine Bunkers" and "Domestic Marine Bunkers" were assessed for all countries in the IEA statistics. The changes from one year to the next could occasionally be very significant. The same number could occasionally also be reported year by year. While this could be valid and reflect actual use in some cases, a high frequency of these occurrences could indicate errors and inaccuracies in the reporting of the consumption of fuel. Typically, the number of these occurrences is higher for countries delivering less fuel. A summary is shown in Tables A1.15 and A1.16.

Table A1.15 *Reporting of International Marine Bunkers to the IEA, 1971–2005*

	Number of countries reporting change in yearly volume > 25% at least once*	Number of changes > 25%	Number of countries reporting identical non-zero figures in sequence
10 largest supplier countries (61% of the reported total)	9 (90%)	63 (18%)	1 (10%)
Next 20 countries (29% of reported total)	17 (85%)	121 (17%)	8 (40%)
Next 44 countries (6% of reported total)	40 (100%)	485 (31%)	27 (59%)

* These typically do not occur in the same year.

Table A1.16 *Reporting of Domestic Marine Bunkers to IEA, 1971–2005*

	Number of countries reporting change in yearly volume > 25% at least once*	Number of changes > 25%	Number of countries reporting identical non-zero figures in sequence
10 largest supplier countries (53% of the reported total)	7 (70%)	46 (13%)	2 (20%)
Next 20 countries (25% of reported total)	10 (50%)	107 (15%)	6 (30%)
Next 44 countries (10% of reported total)	21 (48%)	146 (9%)	16 (36%)

* These typically do not occur in the same year.

A1.45 Variations from one year to the next could be caused by abrupt changes in demand, but may also be the result of changes to definitions and practice in national accounting. Also, to avoid double counting, fuel sales should only be reported once. Therefore, if fuel is sold for use on land but subsequently sold for use by ships, this fuel could avoid registration in the statistics of bunker sales. Also, registration could fail if a fuel is exported and subsequently sold offshore.

A1.46 In 2005, the IEA data show that 55% of world sales of ship fuel occurred in the OECD countries. The OECD share of world sales of ship fuel has declined since 1991, when this share peaked at 65%. The OECD countries report 99% of fuels for fishing. This could indicate that fuel sales to fishing in non-OECD countries are either reported in one of the other categories of ship fuel or are not reported. It is also possible that consumption of fuel for fishing is included in a non-shipping category, such as "forest and agriculture". The latter was previously the practice in the OECD countries.

FUEL CONSUMPTION ACCORDING TO IEA STATISTICAL DATA

A1.47 Data for annual fuel consumption were obtained from the IEA database for all reporting years from 1971 to 2005, the most recent data available [26]. Data from the various categories of fuel for all countries were combined to produce Figure A1.3.

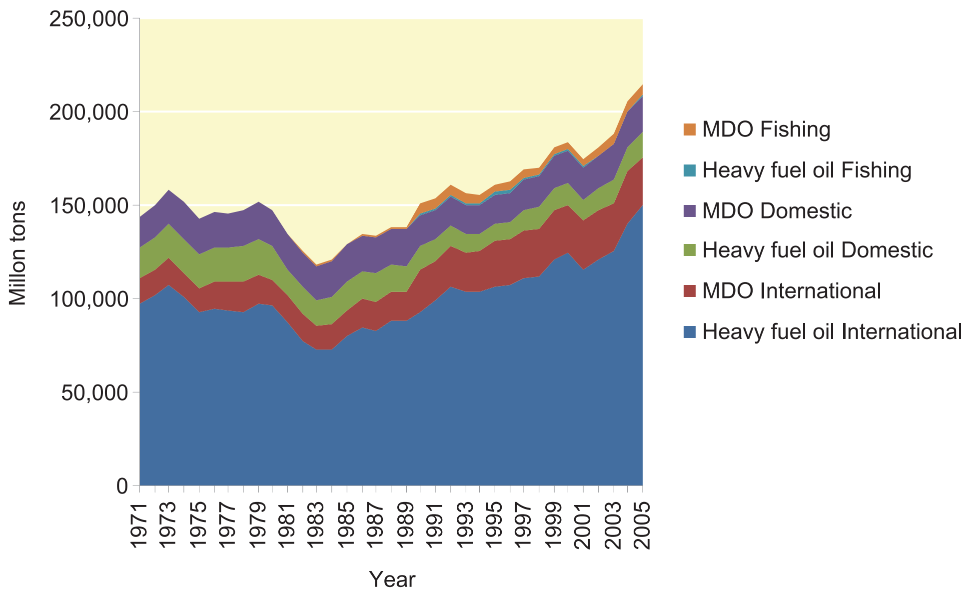


Figure A1.3 *Total fuel consumption by ships (figure based on IEA data)*

A1.48 The total consumption of HFO and MDO fuel for 2005 and the corresponding estimate for 2007 (based on tonne-miles transported) are shown in Table A1.17.

Table A1.17 *IEA ship fuel consumption data (million tonnes) [26]*

		2005	2007 (estimated)
International marine bunkers	HFO	150	159
	MDO	26	27
Domestic navigation	HFO	13	14
	MDO	20	21
Fishing	HFO	0	1
	MDO	5	6
Total		214	234

FUEL CONSUMPTION ACCORDING TO EIA STATISTICAL DATA

A1.49 The EIA provides global statistics for bunkers. Bunkers include fuel that is supplied to ships and to aircraft, both domestic and foreign, consisting primarily of residual and distillate fuel oil for ships and kerosene-based jet fuel for aircraft [27]. The 2000 IMO Study of greenhouse gas emissions from ships concluded that IEA and EIA data were close for OECD countries and that the amount of international jet fuel in the EIA data at that time was limited. Later research has concluded that IEA and EIA data mainly overlap, but differences in estimates for a limited number of countries are significant [29]. A comparison of recent IEA and EIA data is shown in Table A1.18. The IEA data include domestic navigation and fishing. The EIA data are bunkers as per Energy Information Annual [27]. Table A1.18 shows that EIA and IEA data are not very different in magnitude. In these five years, EIA figures are consistently higher on distillate fuels and have the higher total in four out of five years.

Table A1.18 *Comparison of IEA [26] and EIA [27] fuel data (million tonnes)*

Year	Residual		Distillate		Total	
	IEA	EIA	IEA	EIA	IEA	EIA
2000	136	120	48	52	184	172
2001	127	129	47	63	175	192
2002	133	126	48	56	181	182
2003	138	129	50	74	188	202
2004	154	144	51	82	205	226

BACKCASTING AND FORECASTING ESTIMATES OF FUEL CONSUMPTION

A1.50 In order to compare estimates of fuel consumption from different years, it is necessary to adjust the figures to account for developments in world trade and efficiency of transport.

A1.51 Over the past 30 years, a clear and well understood correspondence has been observed between consumption of fuel and seaborne trade in tonne-miles, because the work that is done in global trade is proportional to the energy required (Skjølsvik *et al.*, 2000 [12]; Corbett *et al.*, 2007 [2]; Endresen *et al.*, 2007 [5]). Recent rates of annual growth in total seaborne trade, in tonne-miles, have been 5.2% on average from 2002 to 2007, a lot higher than in past decades (Fearnleys, 2007 [7]). Accordingly, the consumption of fuel from 2001 to 2006 has increased significantly as the total installed power increased by about 25% (Lloyd's Register – Fairplay, 2006 [9]).

A1.52 As shown in the main report, the efficiency of newbuilt ships improves over time. This improvement shows typical steps resulting from developments in technology and market conditions. Between 1985 and 1995, the average efficiency of newbuilt bulk ships and tankers increased while the average efficiency of newbuilt general cargo ships and container ships decreased slightly. The fleet average efficiency has not been calculated; however, the net change is expected to be fairly low in comparison with volumes of trade (measured as tonne-miles), which doubled in the same time-span.

A1.53 Therefore, in order to be able to compare estimates of fuel consumption from different years and also to calculate the emissions series from 1990 to 2007, backcasts and forecasts of point estimates are calculated, based on the annual growth in seaborne trade expressed by annual total freight, in tonne-miles, from Fearnleys [7].

COMPARISON OF ESTIMATES OF CONSUMPTION OF BUNKER FUEL

A1.54 The 2000 IMO study on GHG emissions from ships used statistics for global sales of bunker fuel. Other studies, such as those of Corbett *et al.* [1], Eyring *et al.* [3], the IMO Expert Group [4], and Endresen *et al.* [5], have been based on estimates of ship activity.

A1.55 Estimates of consumption of fuel and of emissions in the above studies are given for different years (2000, 2001, and 2007). In order to be able to compare them with the results from this study (2007), backcasts and forecasts for these point estimates are needed. As outlined in paragraphs A1.50 to A1.53, backcasts and forecasts for these point estimates are calculated from the time evolution of freight tonne-miles from Fearnleys [7]. The result is presented in Figure A1.4, which also shows statistics for international bunker sales [26] and the historical estimates from Eyring *et al.* [3] and Endresen *et al.* [5] from 1950 to 2007. Since some of these studies included emissions from military vessels, the emissions from such vessels have been removed. Also, estimated consumptions for boilers and auxiliary engines are added, where appropriate, to allow just comparison, as shown in Table A1.19.

A1.56 The activity-based consensus estimate from the present study is shown as a blue dot in Figure A1.4. Light blue whisker lines extend from this point to indicate the range of uncertainty given by the

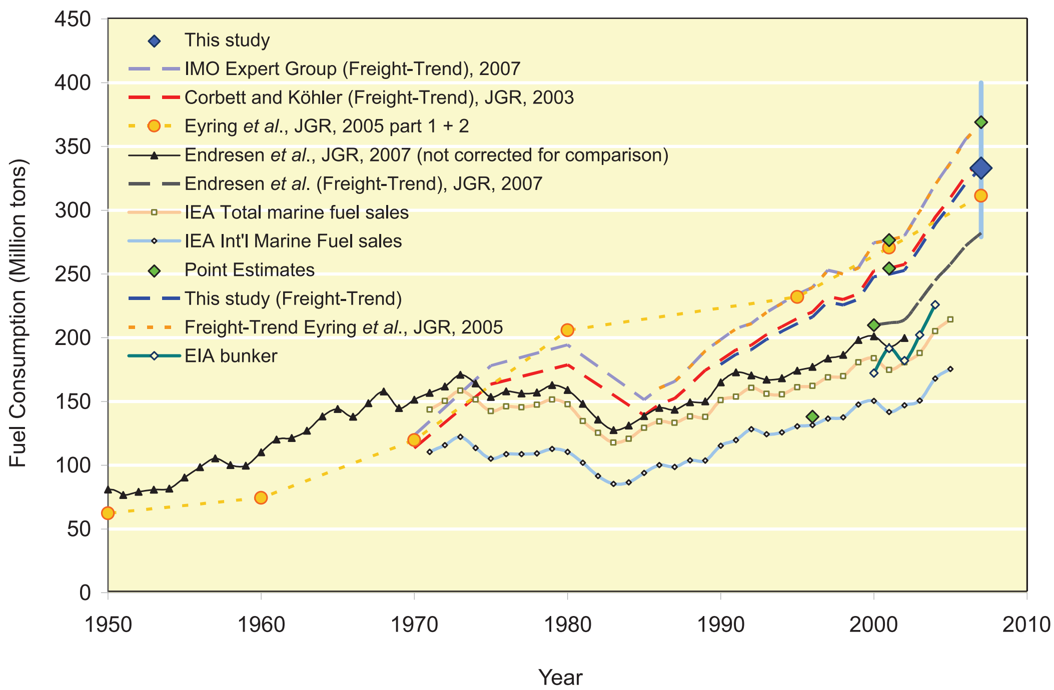


Figure A1.4 *World fleet fuel consumption (except naval vessels) from different activity-based estimates and statistics. Symbols indicate the original estimates for individual years and the solid lines show the original estimates of trend. Dashed lines show the backcast and forecast, calculated from the time evolution of freight tonne-miles with the point estimates. The blue square shows the activity-based estimate from this study and the blue range bar indicates the high and low bound estimates*

Table A1.19 *Corrections that have been applied to enable comparisons with previous inventories*

	Base year	Total (Mt)	Military (Mt)	Auxiliary (Mt)	Boiler (Mt)	Adjusted total (Mt)	2007 (estimated) (Mt)
Eyring *et al.*, 2005 [3]	2001	280	–9.4	Included	5.9*	277	361
Corbett *et al.*, 2003 [1]	2001	289	–40.5	Included	5.9*	254	339
Endresen *et al.*, 2007 [5]	2000	195	Not included	14.9†	5.9*	210	282
IMO Expert Group [4]	2007	369	Not included	Included	Included	369	369
IEA total marine sales	2005	214	Not included	Included	Included	214	234
EIA bunker	2004	225	Not corrected	Included	Included	225	260

* Estimate based on present study.
† Estimate based on Corbett *et al.*, 2003 [1].

high and low bound estimates. As can be seen in this figure, the consensus estimate from the present study is:

1. lower than the estimate from the IMO Expert Group [4], but
2. higher than the estimate based on linearly interpolating 2020 emissions from Eyring *et al.* [3] (military vessels removed); however, the consensus estimate is,
3. lower than forecasts based on Eyring *et al.*[3], using the freight trend method outlined in paragraphs A1.50 to A1.53, and
4. close to the result of Corbett *et al.* when military vessels are removed from the original figures, but
5. higher than the forecast based on Endresen *et al.* (2007) [5].

A1.57 In the case of the Endresen *et al.* (2007) [5], backcast values of the consensus estimate would match around 1985, due to the difference in slope.

DISCUSSIONS

A1.58 The IEA and EIA data mainly overlap, but differences in estimates for a limited number of countries are significant [29]. We reviewed the data entries "International Marine Bunkers" and "Domestic Marine Bunkers" for all countries in the IEA statistics. The compilation of statistics for bunker fuel requires a combination of fuels, reported under different categories (e.g., national or international bunker fuel). This can be challenging on a global scale because most energy inventories follow accounting methodologies that are intended to conform to the International Energy Agency's energy allocation criteria [13] while some statistical sources for marine fuels do not define international marine fuels in the same way [10]. Understanding what portion of the energy that is consumed by ocean shipping is described by statistics for international marine sales requires a historical review of energy cooperation and reporting among nations. This section reviews the relevant background, based on the published history of the International Energy Agency (IEA) and current studies of past marine demand for fuel.

A1.59 The IEA was established in 1974 within the OECD framework, in part, to promote "co-operation with oil producing and other oil consuming countries with a view to developing a stable international energy trade as well as the rational management and use of world energy resources in the interest of all countries" [19]. The IEA Agreement on an International Energy Program (IEP) was designated to be the "focal point for the industrial countries' energy co-operation on such issues as: security of supply, long-term policy, information 'transparency', energy and the environment, research and development and international energy relations" [19].

A1.60 This required the development of energy statistics, particularly for oil supplies that were disrupted during the 1973 oil crisis. Motivated by energy security (including an oil sharing system), these statistics were to be the basis for emergency allocations among signing nations. According to the IEA agreement [19], fuels were to be included within a nation's "oil stocks" if, amongst other conditions, they were (a) in barges; (b) in intercoastal tankers; (c) in oil tankers in port; or (d) in inland ship bunkers. Fuels were to be excluded from domestic stocks if, amongst other conditions, they were (a) in seagoing ships' bunkers or (b) in tankers at sea.

A1.61 International marine fuels statistics were not intended to represent the total energy that is used by ships engaged in global commerce. Rather, these data were used to differentiate those fuels within a nation's domestic stock from those that were not eligible for emergency allocation calculations within the oil emergency sharing system. Specifically, the IEP agreement tasked the Standing Group on Emergency Questions to "consider common rules for the treatment of marine bunkers in an emergency, and of including marine bunkers in the consumption against which stocks are measured" [19]. Later, the IEA clarified that a nation's marine fuel stocks "may not be counted if they are held as international marine bunkers, since such bunkers are treated as exports under a 1976 Governing Board decision incorporated into the Emergency Management Manual (EMM)" [19].

A1.62 Since then, the IEA definitions have been reworded to be more consistent with reporting guidance under IPCC [22]. Currently, the IEA defines "international marine bunkers (fuel) [to] cover those quantities delivered to sea-going ships of all flags, including warships. Consumption by ships engaged in transport in inland and coastal waters is not included." The IEA defines national navigation to be "internal and coastal navigation (including small craft and coastal vessels not purchasing their bunker requirements under international marine bunker contracts). Fuel used for ocean, coastal and inland fishing should be included in agriculture."

A1.63 Because of this terminology, the term "international marine fuel" introduces a classification problem for environmental assessments, because it does not conform to vessel activity data, and also the quality of the data gathered for IEA reporting of sales of ship fuel is inconsistent across nations and over time. For example, non-member countries are not obliged by the IEA treaty to publish data according to their specific methodologies and standards; data collected by IEA for the non-member countries could be less accurate. Inconsistencies in IEA data could be expected to under-report consumption. This is particularly the case with regard to the countries that are not part of the IEA and which do not have the same obligations to report fuel sales in the first place and need not use the same standards and definitions for reporting data.

A1.64 It was observed that the changes from one year to the next occasionally could be very significant, and also that the same number could be reported year by year. A high frequency of these occurrences could indicate errors and inaccuracies in the reporting of consumption of fuel. The total energies represented as "ship fuels" in IEA statistics represent variable quality in reporting by nations, and the classification between international and domestic sales of marine fuels is not reliable.

A1.65 Relying primarily on these classifications leads to a significant error in terms of estimating total energy used by the fleet when historical sales data are misinterpreted as complete energy consumption by ships engaged in international trade (i.e. the fleet of ships in international registries). For example, in work published in 1997 and 1999, Corbett and Fischbeck clearly assumed that sales of international marine fuel represented consumption [23, 15]. The 2000 study of GHGs from ships also used these data in their fuel-based estimates of emissions. Later work produced activity-based methodologies and guidance that identified best practice for calculating updated global estimates [13, 20, 21, 22].

A1.66 In 2003 and 2007, Corbett and Köhler [1] and Endresen *et al.* [5] replaced these sales-based assumptions with activity-based estimates of ship energy requirements that exposed the bias of sales statistics and suggested that the size of the error could range between 25% for cargo ships and a factor of two for the world fleet [1]. Independent work largely confirms the validity of activity-based methodologies [4, 5, 6] (and supports the insight that energy demand of the world marine fleet is the sum of international fuel sales plus domestically assigned fuel sales [5, 6]). Some debate continues about the estimates of global fuel usage within these bounds, but the methodological elements of activity-based inventories are widely accepted.

CONSENSUS ESTIMATE OF ANNUAL EMISSIONS DATA FROM 1990 TO 2007

A1.67 In light of the comparison of previous estimates of fuel consumption and subsequent discussions, the international team of scientists behind this study concluded that the activity-based estimate, with use of detailed activity data, is a more correct representation of the total emissions from ships than what is obtained from the available fuel statistics. Therefore, we agreed (i) that the activity-based estimate should be used as the consensus estimate from this study; (ii) that we could agree on a bounding range of fuel consumption by the fleet and emissions from the fleet that considered the most likely input parameters for activity-based calculations of emissions; and (iii) that we could present a consensus number for use by IMO. Since AIS data are not available for years other than 2007, separate inventories have not been set up for each year. Instead, the historic series of emissions has been constructed by backcasting, as set out in paragraphs A1.50 to A1.53.

A1.68 The consensus of estimates from this study is given in Table A1.20. Tables A1.21 and A1.22 show

Table A1.20 *Consensus estimates of fuel consumption (million tonnes) in 2007*

	Low bound	Best	High bound
Total fuel consumption	279	333	400
International shipping	223	277	344

Table A1.21 *Total fuel consumption (million tonnes) in 2007, by source*

	Low bound	Best	High bound
Residual fuel	215	257	308
Distillate fuel	64	76	92
Slow-speed engines	181	215	259
Medium-speed engines	92	110	132
Boiler	7	8	9

Table A1.22 *Fuel consumption (million tonnes) by international shipping in 2007, by source*

	Low bound	Best	High bound
Residual fuel	172	213	265
Distillate fuel	51	64	79
Slow-speed engines	144	179	223
Medium-speed engines	73	91	113
Boiler	5	7	8

Table A1.23 *Fuel consumption (million tonnes) from 1990 to 2007*

Year	Shipping total			International shipping		
	Low bound	Best	High bound	Low bound	Best	High bound
1990	150	179	215	120	149	185
1991	157	187	224	125	155	193
1992	160	191	229	128	159	197
1993	166	199	239	133	165	205
1994	172	205	246	137	170	212
1995	177	211	254	141	176	218
1996	181	216	260	145	180	223
1997	191	228	274	153	190	236
1998	189	226	271	151	188	233
1999	193	230	276	154	191	238
2000	208	248	298	166	206	256
2001	209	250	300	167	208	258
2002	212	253	304	169	210	261
2003	226	270	325	181	225	279
2004	242	289	347	193	240	298
2005	255	304	365	204	253	314
2006	269	321	385	215	267	331
2007	279	333	400	223	277	344

fuel consumption by source. Series of historic emissions are shown in Table A1.23 and Figure A1.5. Fuel consumption, split by ship categories, with uncertainty bars, is presented in Figure A1.6. Fuel consumption, split by coastwise/ocean-going type of operation and high-level ship categories, is given in Figure A1.7 and Table A1.24.

GEOGRAPHIC DISTRIBUTION OF SHIP TRAFFIC AND EMISSIONS

INTRODUCTION

A1.69 Global inventory estimates for fuel use or of emissions that are derived from activity-based bottom-up estimates or from statistics for fuel sales are distributed according to a calculated ship traffic intensity proxy per grid cell, referring to the relative ship reporting frequency or relative ship reporting frequency weighted by the ship size. The accuracy of the resulting totals is limited by uncertainty in global estimates, as discussed above, and the representative bias of spatial proxies limits the accuracy of assignment (spatial precision) of emissions.

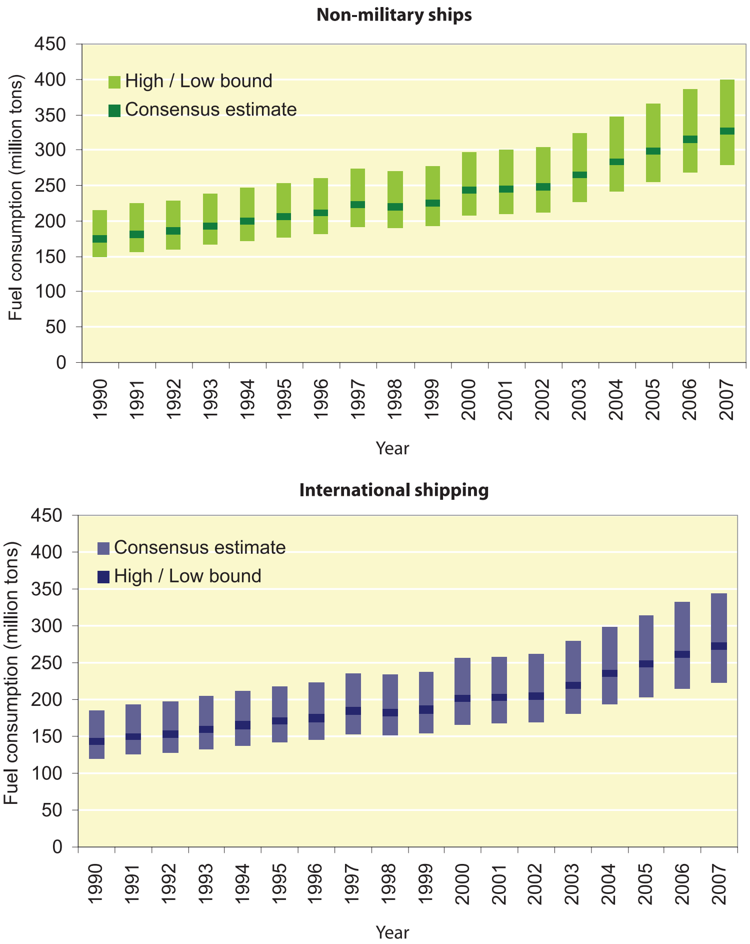


Figure A1.5 *Consensus estimates of fuel consumption from 1990 to 2007*

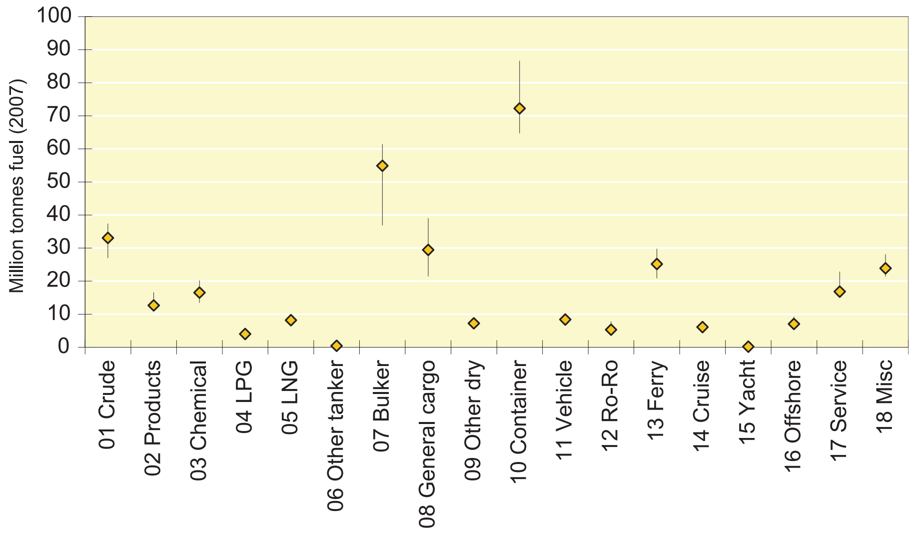


Figure A1.6 *Estimated fuel consumption (million tonnes) in 2007 by main ship categories, with uncertainty bars*

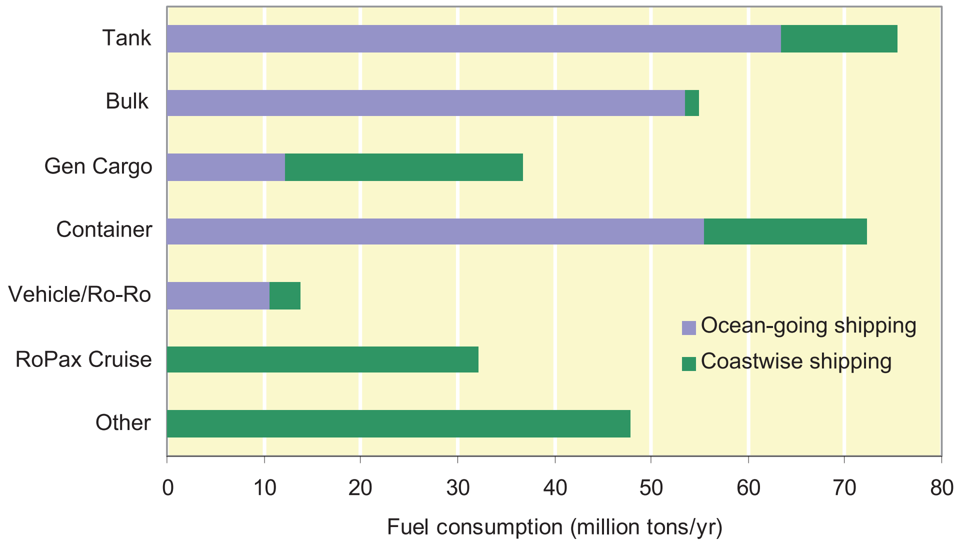


Figure A1.7 *Fuel consumption (million tonnes) by main ship categories, showing assumed typical types of operation (Coastwise shipping is mainly ships < 15,000 dwt, RoPax, Cruise, Service and Fishing)*

Table A1.24 *Activity-based estimate of fuel use in 2007*

	Oceangoing	Coastwise	Other	Total
Bulk	54	1	0	55
Container	55	17	0	72
General cargo	12	25	0	37
Other	0	0	48	48
RoPax/Cruise	0	31	0	31
Tank	63	12	0	75
Vehicle/Ro-Ro	11	3	0	14
Grand total	195	89	48	333

SPATIAL PROXIES OF GLOBAL SHIP TRAFFIC

A1.70 Corbett *et al.* (1997) produced one of the first global spatial representations of ship emissions, using a shipping traffic intensity proxy derived from the Comprehensive Ocean-Atmosphere Data Set (COADS); this is a dataset of voluntarily reported ocean and atmospheric observations with ship locations, which is freely available. Endresen *et al.* (2003) [6] improved the global spatial representation of ship emissions by using ship size (gross tonnage)-weighted reporting frequencies from the Automated Mutual-assistance Vessel Rescue system (AMVER) dataset. AMVER, sponsored by the United States Coast Guard (USCG), holds detailed voyage information, based on daily reports for different ship types. Participation in AMVER was, until very recently, limited to merchant ships over 1,000 GT on a voyage for 24 or more hours and the data are strictly confidential. The participation in AMVER is 12,550 ships, but only around 7,100 ships have actually reported. Endresen *et al.* (2003) [6] observed that COADS and AMVER lead to very different regional distributions. Wang *et al.* (2007) addressed the potential statistical and geographical sampling bias of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS) and the AMVER datasets, which are the two most appropriate global ship traffic intensity proxies, and used ICOADS to demonstrate a method to improve the representativeness of global proxies by trimming over-reporting vessels; this mitigates the sampling bias, augments the sample dataset, and accounts for ship heterogeneity.

Table A1.25 *Summary of results from consensus estimate fuel oil consumption (thousand tonnes) calculations*

Category	Size/Type	*	Ship: Average fuel oil consumption (thousand tonnes) Main Engine	Aux Engine	Boiler	Total	Category: Total fuel oil consumption (thousand tonnes) Main Engine	Aux Engine	Boiler	Total
Crude oil tanker	200,000+ dwt	O	21.8	1.2	1.3	24.3	10,760.2	607.1	617.5	11,984.8
Crude oil tanker	120,000–199,999 dwt	O	16.5	1.5	0.9	18.8	5,810.8	516.6	317.7	6,645.1
Crude oil tanker	80,000–119,999 dwt	O	12.2	1.0	3.0	16.1	7,912.8	621.8	1,953.0	10,487.7
Crude oil tanker	60,000–79,999 dwt	O	8.2	0.8	3.0	12.0	1,480.2	145.3	540.0	2,165.5
Crude oil tanker	10,000–59,999 dwt	O	6.2	0.8	1.5	8.5	1,506.4	196.8	366.8	2,070.0
Crude oil tanker	0–9,999 dwt	C	1.1	0.2	0.5	1.8	122.4	27.9	57.0	207.3
Products tanker	60,000+ dwt	O	7.7	1.0	3.6	12.2	1,520.0	191.9	712.8	2,424.8
Products tanker	20,000–59,999 dwt	O	4.5	0.9	3.0	8.4	2,050.2	416.6	1,366.5	3,833.3
Products tanker	10,000–19,999 dwt	O	2.9	0.6	1.8	5.3	562.4	113.6	346.5	1,022.5
Products tanker	5,000–9,999 dwt	C	1.8	0.3	0.9	3.0	821.3	149.3	419.0	1,389.5
Products tanker	0–4,999 dwt	C	0.6	0.1	0.3	1.0	2,288.2	536.3	1,187.7	4,012.2
Chemical tanker	20,000+ dwt	O	8.5	1.0	0.0	9.5	8,574.1	1,004.0	0.0	9,578.1
Chemical tanker	10,000–19,999 dwt	O	4.7	0.7	0.0	5.4	2,771.6	401.7	0.0	3,173.3
Chemical tanker	5,000–9,999 dwt	C	3.0	0.5	0.0	3.5	1,924.4	294.6	0.0	2,219.0
Chemical tanker	0–4,999 dwt	C	0.7	0.2	0.0	1.0	1,199.7	395.1	0.0	1,594.8
LPG tanker	50,000+ cbm	O	12.1	1.2	0.0	13.3	1,666.3	164.7	0.0	1,830.9
LPG tanker	0–49,999 cbm	C	1.9	0.5	0.0	2.3	1,749.7	453.6	0.0	2,203.4
LNG tanker	200,000+ cbm	O	28.5	3.8	0.0	32.4	114.2	15.3	0.0	129.4
LNG tanker	0–199,999 cbm	O	31.1	2.8	0.0	33.8	7,411.6	657.3	0.0	8,068.9
Other tanker	Other	C	0.9	0.2	0.0	1.1	351.8	93.1	0.0	445.0
Bulk	200,000+ dwt	O	15.2	1.2	0.0	16.4	1,811.0	140.8	0.0	1,951.8
Bulk	100,000–199,999 dwt	O	13.1	1.0	0.0	14.1	8,982.5	712.4	0.0	9,694.9
Bulk	60,000–99,999 dwt	O	8.8	0.8	0.0	9.6	13,314.0	1,237.4	0.0	14,551.4
Bulk	35,000–59,999 dwt	O	7.0	0.8	0.0	7.8	13,122.5	1,397.3	0.0	14,519.8
Bulk	10,000–34,999 dwt	O	5.4	0.7	0.0	6.1	11,353.5	1,479.7	0.0	12,833.2
Bulk	0–9,999 dwt	C	0.9	0.3	0.0	1.2	987.1	350.9	0.0	1,338.0
General cargo	10,000+ dwt	O	5.8	0.6	0.0	6.3	3,877.2	378.2	0.0	4,255.5
General cargo	5,000–9,999 dwt	C	3.1	0.3	0.0	3.5	4,801.9	487.0	0.0	5,288.9
General cargo	0–4,999 dwt	C	0.5	0.1	0.0	0.6	6,036.4	1,038.3	0.0	7,074.7

Table A1.25 *Continued*

Category	Size/Type	*	Ship: Average fuel oil consumption (thousand tonnes) Main Engine	Category: Total fuel oil consumption (thousand tonnes) Aux Engine	Boiler	Total	Main Engine	Aux Engine	Boiler	Total
General cargo	10,000+ dwt, 100+ TEU	O	5.8	0.7	0.0	6.5	7,055.0	869.9	0.0	7,925.0
General cargo	5,000–9,999 dwt, 100+ TEU	C	2.1	0.4	0.0	2.6	2,332.0	458.1	0.0	2,790.2
General cargo	0–4,999 dwt, 100+ TEU	C	1.1	0.4	0.0	1.4	1,590.5	542.5	0.0	2,133.0
Other dry	Reefer	C	4.3	0.7	0.0	5.0	5,348.9	813.0	0.0	6,161.9
Other dry	Special	C	4.1	0.6	0.0	4.8	944.1	139.0	0.0	1,083.0
Container	8,000+ TEU	O	46.4	5.9	0.0	52.3	5,457.1	688.1	0.0	6,145.2
Container	5,000–7,999 TEU	O	37.5	4.6	0.0	42.1	15,647.1	1,928.8	0.0	17,575.9
Container	3,000–4,999 TEU	O	25.2	2.8	0.0	28.0	17,904.9	2,006.5	0.0	19,911.4
Container	2,000–2,999 TEU	O	15.6	2.2	0.0	17.7	10,386.9	1,436.3	0.0	11,823.2
Container	1,000–1,999 TEU	C	9.7	1.4	0.0	11.1	10,859.8	1,565.3	0.0	12,425.1
Container	0–999 TEU	C	3.1	0.8	0.0	3.9	3,466.3	882.1	0.0	4,348.3
Vehicle	4,000+ ceu	O	13.2	1.1	0.0	14.4	5,263.2	456.1	0.0	5,719.3
Vehicle	0–3,999 ceu	O	7.3	0.7	0.0	8.0	2,472.6	224.7	0.0	2,697.3
Ro-Ro	2,000+ lm	O	10.0	1.2	0.0	11.2	1,931.7	238.5	0.0	2,170.1
Ro-Ro	0–1,999 lm	C	1.7	0.4	0.0	2.1	2,561.7	573.9	0.0	3,135.6
Ferry	Pax Only, 25 kn+	C	2.6	0.1	0.0	2.7	2,566.5	70.0	0.0	2,636.5
Ferry	Pax Only, <25 kn	C	1.2	0.1	0.0	1.3	2,592.7	199.8	0.0	2,792.5
Ferry	RoPax, 25 kn+	C	18.3	1.1	0.0	19.4	3,241.4	193.3	0.0	3,434.7
Ferry	RoPax, <25 kn	C	4.5	0.7	0.0	5.2	14,259.5	2,053.2	0.0	16,312.7
Cruise	100,000+ gt	C	47.5	2.0	0.0	49.5	1,141.1	47.9	0.0	1,189.0
Cruise	60,000–99,999 gt	C	32.6	4.3	0.0	36.9	2,247.1	300.1	0.0	2,547.2
Cruise	10,000–59,999 gt	C	12.5	2.4	0.0	14.8	1,620.0	307.8	0.0	1,927.9
Cruise	2,000–9,999 gt	C	3.2	1.0	0.0	4.2	237.0	72.3	0.0	309.3
Cruise	0–1,999 gt	C	0.5	0.2	0.0	0.7	109.8	40.2	0.0	150.1
Yacht	Yacht	N	0.6	0.2	0.0	0.8	590.7	205.7	0.0	796.4
Offshore	Crew/supply vessel	N	0.7	0.1	0.0	0.8	445.3	57.9	0.0	503.2
Offshore	Platform supply	N	0.7	0.4	0.0	1.1	1,251.3	652.9	0.0	1,904.2
Offshore	Tug/supply ship	N	0.5	0.3	0.0	0.8	290.0	165.9	0.0	455.9
Offshore	Anchor handling T/S	N	1.6	0.7	0.0	2.3	1,895.4	814.7	0.0	2,710.1

Offshore	Support/safety	N	0.8	0.3	0.0	1.1	394.9	140.5	0.0	535.4
Offshore	Pipe (various)	N	1.2	0.9	0.0	2.1	287.8	228.1	0.0	515.8
Service	Research	N	1.1	0.4	0.0	1.5	954.9	391.3	0.0	1,346.3
Service	Tug	N	0.8	0.1	0.0	0.9	9949.8	1,170.2	0.0	11,120.0
Service	Dredging	N	1.0	0.5	0.0	1.5	1,172.1	617.5	0.0	1,789.6
Service	SAR & patrol	N	0.6	0.2	0.0	0.8	627.3	199.9	0.0	827.2
Service	Workboats	N	0.4	0.2	0.0	0.6	434.2	221.8	0.0	656.0
Service	Other	N	1.1	0.2	0.0	1.3	903.4	187.7	0.0	1,091.1
Miscellaneous	Fishing	N	0.3	0.2	0.0	0.5	3,599.5	2,928.6	0.0	6,528.1
Miscellaneous	Trawlers	N	0.8	0.4	0.0	1.2	7,565.5	4,303.7	0.0	11,869.2
Miscellaneous	Other fishing	N	1.3	0.3	0.0	1.6	1,685.8	422.8	0.0	2,108.6
Miscellaneous	Other	N	4.2	0.9	0.0	5.1	2,796.4	600.1	0.0	3,396.5

* Ship size categories: O = Ocean-going shipping; C = Coastwise shipping; N = Non-transport shipping (modelled as "coastwise"). Note that all container ships, of all sizes, are modelled as "container" in the scenarios.

Please note that the uncertainty of the estimate of individual ship categories is higher than the estimated total.

A1.71 In this first phase of the project, calculations are not affected by the geographic distribution of the emissions. However, as a reference, global ship traffic patterns are illustrated in Figure A1.8.

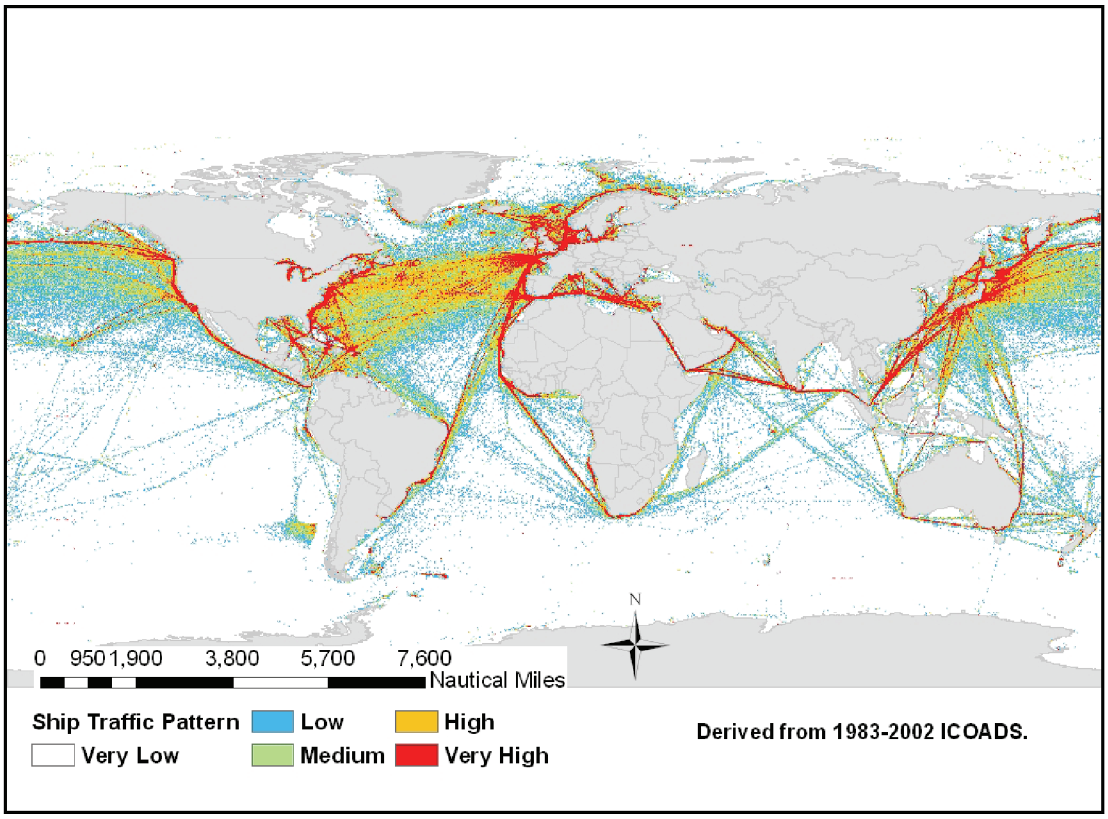


Figure A1.8 *Ship traffic patterns, based on ICOADS data*

REFERENCES

1 Corbett, J.J., and Köhler, H.W. 2003. "Updated emissions from ocean shipping". *J. Geophys. Res.*, 108: D204650, doi:10.1029/2003JD003751.

2 Corbett, J.J., Firestone, J. and Wang, C. 2007. "Estimation, validation, and forecasts of regional commercial marine vessel inventories", Final Report for the California Air Resources Board and the California Environmental Protection Agency and for the Commission for Environmental Cooperation in North America, ARB Contract Number 04–346.

3 Eyring, V., Köhler, H.W., van Aardenne, J. and Lauer, A. 2005. "Emissions from International Shipping: 1. The last 50 Years". *J. Geophys. Res.*, 110: D17305, doi:10.1029/2004JD005619.

4 Input from the four subgroups and individual experts to the final report of the Informal Cross Government/ Industry Scientific Group of Experts, IMO documents BLG 12/INF.10 and BLG 12/6/1.

5 Endresen, Ø., Sørgård, E., Behrens, H.L., Brett, P.O. and Isaksen, I.S.A. 2007. "A historical reconstruction of ships' fuel consumption and emissions". *J. Geophys. Res.*, 112: D12301, doi:10.1029/2006JD007630.

6 Endresen, Ø., Sørgård, E., Sundet, J.K., Dalsøren, S.B., Isaksen, I.S.A., Berglen, T.F. and Gravir, G. 2003. "Emission from international sea transportation and environmental impact". *J. Geophys. Res.*, 108: D174560, doi:10.1029/ 2002JD002898.

7 Fearnleys, 2007. *Fearnleys Review 2007, The Tanker and Bulk Markets and Fleets*, Oslo, Norway.

8 Gunner, T. 2007 "Shipping, CO_2 and other Air Emissions", Technical workshop meeting on emissions from aviation and maritime transport, Oslo, Norway, October 2007. http://www.eionet.europa.eu/training/bunkerfuelemissions

9 Lloyd's Register – Fairplay (LRF). 2006. Extracts from the World merchant fleet database for 2001 to 2006 (all civil ocean-going cargo and passenger ships above or equal to 100 GT), provided by Lloyd's, UK.

10 Olivier, J.G.J. and Peters, J.A.H.W. 1999. "International marine and aviation bunker fuel: trends, ranking of countries and comparison with national CO_2 emissions". Netherlands Environmental Assessment Agency. RIVM report 773301 002.

11 Olivier, J.G.J., Berdowski, J.J.M., Peters, J.A.H.W., Bakker, J., Visschedijk, A.J.H. and Bloos, J.P.J. 2001. "Applications of EDGAR. Including a description of EDGAR 3.0: reference database with trend data for 1970–1995". RIVM, Bilthoven. RIVM report number 773301 001/NOP report number 410200 051.

12 Skjølsvik, K.O., Andersen, A.B., Corbett, J.J. and Skjelvik, J.M. 2000. "Study of greenhouse gas emissions from ships" (MEPC 45/8 Report to International Maritime Organization on the outcome of the IMO Study on Green-

house Gas Emissions from Ships. MARINTEK Sintef Group, Carnegie Mellon University, Center for Economic Analysis, and Det Norske Veritas: Trondheim, Norway).

13 Thomas, R., Lauretis, R.D., Fontelle, J.-P., Hill, N., Kilde, N. and Rypdal, K. 2002. Shipping Activities, Chapter B842, in EMEP/CORINAIR Emission Inventory Guidebook – October 2002 UPDATE, edited by K. Lavender, G. Reynolds, A. Webster, and K. Rypdal, European Environment Agency, Copenhagen, Denmark.

14 Wang, C., Corbett, J.J. and Firestone, J. 2008. “Improving spatial representation of global ship emissions inventories”. *Environmental Science & Technology*, 42: 193–199, doi:10.1021/es0700799.

15 Corbett, J.J. and Fischbeck, P.S. 1997. “Emissions from ships”. *Science*, 278(5339): 823–824, doi:10.1126/science.278.5339.823.

16 Data provided by Lloyd’s Register – Fairplay Research, Sweden.

17 Data compiled by DonChool Lee, Mpoko National Maritime University, Korea.

18 Diesel & Gas Turbine Worldwide 2005. Diesel & Gas Turbine Publications. 20855 Watertown Road, Suite 220, Waukesha, WI 53186, USA.

19 Scott, R. 1994. *IEA: The First Twenty Years*. Paris, France, Organisation for Economic Co-operation and Development (OECD).

20 ICF Consulting. 2005. “Best Practices in Preparing Port Emission Inventories: draft for review”. Browning, L. and Bailey, K. Fairfax, Virginia, Prepared for Office of Policy, Economics and Innovation, United States Environmental Protection Agency. 39 pp.

21 UNFCCC and Subsidiary Body for Scientific and Technological Advice. 2004. “Methodological issues relating to emissions from international aviation and maritime transport; Note by the secretariat”. Prepared for 20th session, 16–25 June 2004, Bonn, Germany. United Nations Framework Convention on Climate Change, Subsidiary Body for Scientific and Technological Advice. Document FCCC/SBSTA/2004/INF.5.

22 International Energy Agency. 1987. Energy Statistics 1970–1985 and Main Series from 1960. Paris, France, Organisation for Economic Co-operation and Development.

23 Houghton, J., Meira Filho, L. *et al.*, editors. 1997. Revised 1996 IPCC Guidelines for National Greenhouse Gas Inventories. Bracknell, UK, IPCC WGI Technical Support Unit.

24 Corbett, J.J. and Fischbeck, P.S. 2000. “Emissions from waterborne commerce vessels in United States continental and inland waterways”. *Environmental Science & Technology*, 34: 3254–3260.

25 CIMAC – International Council of Combustion Engines http://www.cimac.com

26 IEA Data Services, 2007 Energy Balances and Energy Statistics for OECD and non-OECD Countries.

27 Energy Information Administration International Energy Annual, Table 31 – various years: http://www.eia.doe.gov/

28 IMO. International Convention for the Safety of Life at Sea (SOLAS), 1974. Chapter V – Safety of navigation.

29 Endresen, Ø., Bakke, J., Sørgård, E., Berglen, T.F. and Holmvang, P. 2005. “Improved modelling of ship SO_2 emissions – a fuel-based approach”. *Atmospheric Environment*, 39: 3621–3628.

Appendix 2

Emission-reduction technology options

INTRODUCTION

A2.1 This appendix provides information on emission reduction through energy savings, alternative energy and fuel options as additional background to the discussions in Chapter 5 in the main report. Possible future use of these technologies and fuels in the light of SRES scenarios is discussed in Chapter 7.

ENERGY LOSSES ON BOARD SHIP

A2.2 Only a fraction of the fuel energy going into the ship's main engines actually ends up generating propulsion thrust. This is illustrated in Figure A2.1, which represents a small well-maintained cargo ship moving at about at 15 knots in Beaufort 6 head weather condition. The bottom bar in this diagram represents the energy input to the main engine from the fuel. In this case, 43% of the fuel energy is converted into shaft power while the remaining energy is lost in the exhaust or as heat losses. Due to further losses in the propeller and transmission, only 28% of the energy from the fuel that is fed to the main engine generates propulsion thrust in this example. The rest of the energy ends up as heat, as exhaust, and as transmission and propeller losses. The majority of these remaining 28% are spent overcoming hull friction, while the remaining energy is spent in overcoming weather resistance and air resistance, as residual losses and for generating waves. Additional to this is the fuel energy for operation of auxiliary engines. Ships other than the case shown will have the same types of losses; however, the relative sizes will differ.

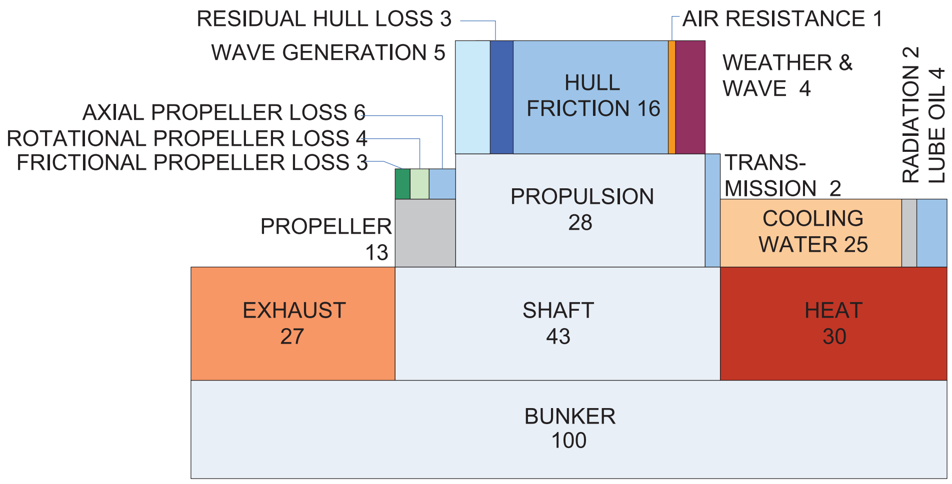


Figure A2.1 *Use of propulsion energy on board a small cargo ship, head sea, Beaufort 6*

A2.3 The potential for improvement in an area is related to the losses in the various areas. For instance, hull friction is an important area for tankers and bulk ships. Generally, propeller losses decrease at reduced speed while the proportion of frictional resistance increases relative to other losses. Operating speed and operation profile may thus influence which areas constitute the larger loss areas. Naturally, the available space on deck and in machinery compartments as well as weight/stability margins may restrict the possibilities for installing additional equipment. Therefore, the possibility to use various techniques, the potential for improvement and the associated cost-effectiveness are very variable between ships and ship types.

A2.4 Hull fouling will increase the frictional losses and reduce the speed that is attained at a given power. Propeller fouling will reduce the efficiency of the propeller. Engine fouling, wear and non-optimal balancing and adjustment will contribute to reduction of shaft power and higher heat losses. Options to improve the ship principally aim to reduce these losses, while the aim of maintenance actions is to prevent these losses from increasing.

Table A2.1 *Distribution of energy losses (%) in selected case ships*

	Tanker/bulk		Container		General cargo		RoPax	
Speed (knots)	15.6	10.9	21.2	15.5	13.4	9.5	20.1	14.7
Bunker	100	100	100	100	100	100	100	100
Engine								
Exhaust	25.5	28.4	25.0	28.0	25.5	28.4	25.5	28.4
Shaft	49.3	45.4	50.5	46.5	49.3	45.4	49.3	45.4
Heat	25.2	26.2	24.5	25.5	25.2	26.2	25.2	26.2
Propulsion								
Propeller loss	16.3	14.3	15.6	13.0	19.7	15.3	15.5	14.4
Propulsion power	32.1	30.2	33.7	32.4	28.1	28.8	32.6	29.9
Transmission loss	1.0	0.9	1.3	1.2	1.5	1.4	1.2	1.1
Propeller								
Axial loss	6.3	5.3	4.8	3.5	8.8	5.6	4.8	4.3
Rotational loss	3.9	3.4	5.3	3.9	6.0	4.5	5.0	4.7
Frictional loss	6.0	5.7	5.5	5.6	4.9	5.2	5.7	5.4
Hull								
Wave generation	6.4	4.1	8.6	3.9	12.8	5.9	5.3	3.9
Air resistance	0.6	0.6	1.0	1.1	0.7	1.0	1.0	0.9
Hull friction	16.2	16.6	13.9	15.6	8.3	12.0	15.9	14.7
Residual resistance	2.7	1.9	1.8	1.4	2.8	3.2	2.2	1.4
Weather and waves	6.2	6.9	8.4	10.3	3.5	6.7	8.3	9.1

A2.5 The calculation methodology to derive this table is presented in Appendix 3.

POWER TRANSMISSION

A2.6 Thrust is generated by the propeller. High propulsive efficiency is obtained with a large propeller rotating at a low number of revolutions per minute. Ideally, the number of blades should be minimized to reduce blade area and frictional resistance. The size of the propeller may be limited by the ship design, by draught restrictions in expected areas of operation of the ship or by the engine torque. The energy can be transmitted from the engine to the propeller by different means, at different efficiencies:

- Direct mechanical drive – only possible for low-speed engines ($\eta \sim 0.99$);
- Mechanical drive with speed-reduction gearbox ($\eta \sim 0.95$);
- Direct electric drive (generator–cable–motor) ($\eta \sim 0.90$); and
- Speed-controlled electric drive "all-electric ship" (generator, frequency converter, switchboard, frequency converter, motor) ($\eta \sim 0.85$).

A2.7 Currently, direct drive is used on virtually all ships with low-speed two-stroke engines. These include all larger ships and many smaller cargo ships. Medium-speed engines are predominantly used on small vessels and a few larger vessels where space restrictions are severe, such as RoPax vessels. Electric propulsion is only used where other needs predominate, such as dynamic positioning, the need for low vibration and special arrangements and constraints on the location of machinery. In general, due to the transmission losses, electric propulsion systems are not less energy-efficient than comparable direct-drive systems.

POWER GENERATION

A2.8 Power on board is generated either by low-speed or medium-speed diesel engines except for very special cases. The thermal efficiency of engine types in relation to power is indicated in Table A2.2. These figures clearly indicate the low efficiency of even large (in a ship context) gas turbines in combined cycles.

Table A2.2 *Maximum thermal efficiency obtainable with current ship engine systems [5]*

	Small (2 MW)	Medium (10 MW)	Large (30 MW)
Low-speed diesel	~47%	~50%	~53%
Medium-speed diesel	~43%	~47%	~50%
Gas turbine	–	~32%	~35%
Gas turbine combined cycle	–	–	~40%
Steam turbine	–	–	~32 %

A2.9 The same is the case for propulsion by a steam turbine. Therefore, these technologies will remain of interest only for very special applications where energy efficiency is sacrificed for other benefits.

A2.10 Additional to the power that is needed for propulsion, electric power is needed to sustain the crew (the hotel load) as well as various auxiliary systems, such as pumps for cooling water, fans for ventilation, control and navigational systems, etc. Most merchant ships have transverse bow thrusters, for manoeuvring at low speeds, which need significant electrical power, but they are used only for short periods of time. Some ships also have cargo gear (gantry cranes) on board, requiring high power during loading and unloading operations in ports. Passenger ferries and cruise ships will have significant power demand for passenger accommodation, ventilation and air conditioning. Significant heat demands may also be required for passenger comfort and for the production of fresh water.

A2.11 In certain cases, the cargo requires cooling to maintain quality, such as refrigerated or frozen cargo. Certain cargoes, such as special crude oils, heavy fuel oils, bitumen and others, require heating. Some of this heat can be supplied by steam generators based on heat from exhaust gases (utilizators); however, in many cases, an additional steam boiler is needed to supply sufficient steam. Steam from exhaust gas is generally sufficient for heating of the heavy fuel oil that is used on most ships during the ship's voyage; however, in port, steam is required from an auxiliary boiler.

DESIGN IMPROVEMENTS

Optimization of hull and of propeller

A2.12 An optimization procedure concerning the wetted hull surface and propeller is a well-known abatement option that is regularly applied to new ship designs in order to achieve reduction of drag (resistance) from the perspective of the hydrodynamic research community. An illustrative example of applied optimization on new design hull forms is a fast (40 knots) displacement monohull ship with high L/B ratio (up to 9:1), based on the principle of wave piercing. There are, in fact, several existing superslender monohull designs with outriggers (see Figure A2.2a) world-wide, development of which started in the early 1990s with the "EuroExpress – Ro-Ro" project by STX Europe [29] (formerly Aker Yards Oy, Kvaerner Masa-Yards).

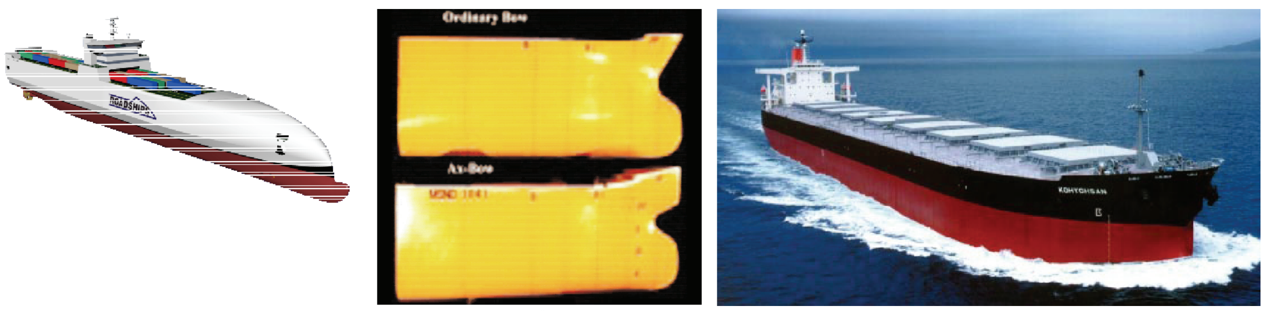
A2.13 In order to achieve reduction of drag (resistance) through optimization, it is necessary to find adequate approaches which will ensure the validity of optimal design from a global perspective, allowing detailed and refined optimization of hydrodynamic design. On the other hand, an alternative approach which allows for complete optimal design is also possible. The main difference of this kind of approach in respect to the first one lays in the ability to define several conflicting tasks, and yet arrive at an optimum solution which best suits optimal ship design in respect to her involvement in a specified operational mode. In spite of the fact that the second approach clearly shows advantages, it should be emphasized that the methods that are applied mostly rely on CFD modelling, and consequently on the experimental results from a towing tank that are used, amongst other purposes, also for validation of theoretical results from CFD.

A2.14 The percentage of new designs that are subjected to systematic optimization of the hull and of the propeller compared to the percentage of designs that are built merely on the basis of existing experience is currently unknown. However, in general, it is believed that probably the greater proportion of new designs today are going through some systematic form of optimization of hull and propeller design, focusing on reduced resistance (drag reduction) and increased propulsive efficiency. The actual proportion of the world fleet is not known. Such optimization requires expertise, and it is probable that many of the "optimization" procedures performed do not really provide an optimum design for all of a ship's operational modes as the end result. Therefore, it is almost impossible to quantify the abating potential, on a world fleet basis, of applying hull and propeller optimizing procedures systematically.

A2.15 There are many barriers to focusing solely on modifying the hull lines to achieve more favourable resistance. Examples are the effects of the given requirements of the amount and type of payload and the dimensions of ports and terminals. These barriers will considerably reduce the potential for the reduction of resistance and of fuel consumption. On single ships, improvements in power requirements of up to 30% have, in fact, occasionally been achieved on particularly ill-conceived designs; however, the mean potential for improvement would be expected to be small. Smaller ships are more sensitive to design details, since they have comparatively large wave-generating resistance and also because less resources will traditionally be available for optimization, due to the smaller overall budget that is typically available for developing the designs.

A2.16 Resistance and energy consumption increase when the hull is in water on which there are waves. Traditionally, ships have been optimized primarily for the still-water conditions in a towing tank (not least because the contractual measurements of trial performance are conducted in still water); however, optimization for irregular wave conditions is becoming more common. During their lifetime, ships will more frequently operate in a wave field that is characterized by the short wavelength λ (small sea states) in comparison to the ship length L. Therefore, optimization for waves generally emphasizes short-wavelength waves [17].

A2.17 One example is development of the so-called "beak bow" at Osaka University. This particular design of bow was implemented on ships with a high block coefficient C_B (tankers, bulk carriers), in order to reduce the wave-added resistance [14]. The waterline curve of an ordinary bow is significantly altered with the introduction of a beak bow. The altered bow design has a more pointed (sharp) shape than the ordinary bow design. However, the original beak-bow design was not satisfactory from a practical point of view since it significantly increases the overall ship length (LOA), which makes the particular ship too long to enter some ports. Therefore, the original beak-bow design has been altered, during the process of practical implementation, into an axe-bow design (see Figure A2.2b). In comparison to the original



(a) (b) (c)

Figure A2.2 *(a) Example of a superslender monohull with outriggers (copyright STX Europe, 2008); (b) Axe-bow design; and (c) 172,000 DWT Capesize bulk carrier* Kohyohsan*, built with an axe bow for Mitsui O.S.K. Lines, Ltd in 2001.*

beak-bow design, it should be noted that the shape at the waterline remains the same, which means that the estimates of effective power are not influenced by the practical modification.

A2.18 One barrier to the widespread usage of such improvements of design is that designs may be owned by specific yards. Also, as already mentioned, performance in waves is not part of the standard test conditions, and, as discussed under hull friction, assessing the performance of ships at sea is challenging; it may not be easy to see the improvement that results from such optimization.

A2.19 Optimization of the superstructure of ships for reduced resistance to still air and to wind has traditionally not been an important subject. Again, there are barriers, in the form of requirements for and the usage of covered spaces. However, for ships with large superstructures and for ships operating at relatively high speeds, there will be a potential for reduction of power consumption by carrying out systematic streamlining of the superstructure to the greatest possible extent. For these ships, it is estimated that there is potential for reduction in power consumption of 2–5%, depending on the size of the superstructure and the area in which the ship operates. Also, for other ships, there is expected to be a certain potential for reduction in power consumption, perhaps in the order of 1–2%, by keeping the topsides as uncluttered and streamlined as possible. The efforts to achieve reductions may range from the simple (such as grinding weld beads flat) to the more extensive (for example, redesigning and repositioning cranes, applying spoilers to alter the airflow over the funnel and deck-houses, and designing more streamlined deck-houses).

A2.20 The main abating effect of optimization of the propeller is obtained by increasing the diameter of the propeller and reducing the number of its revolutions per minute (RPM). The requirements to maintain adequate clearances between the propeller and the hull and to attain sufficient submersion of the propeller when the ship is operating in a seaway and/or in ballast condition set restrictions on the extent to which the diameter of a propeller can be increased. A propeller that is operating at a low number of revolutions per minute may require the additional cost of installing a reduction gear, while propellers operating at a higher number of revolutions per minute can generally be directly connected to the main engine. Propellers with a large diameter, operating at a low number of revolutions per minute, will therefore be best suited to deep-draught ships; this includes most tankers and bulk carriers and many general cargo vessels. Such propellers will be less suited to many container vessels, and they will not, in general, be suited to RoPax vessels or cruise vessels.

A2.21 Podded (azipod) drives are systems where an electric motor with a propeller is suspended under the appropriate (usually the aft) section of the hull. The pod can be rotated to direct the thrust, resulting in very good ship manoeuvrability. In many cases, more than one pod is used. New pod drives have pulling propellers, that face forward. This gives the pod a good flow of water into the pod, resulting in high propulsion efficiency. However, the pod in itself increases the drag, thus reducing total efficiency. Experience from tests of hulls in the towing tank at MARINTEK clearly indicates that the net effect of podded propulsion on the energy efficiency of propulsion is generally negative when compared to conventional designs of propulsion systems.

OPTIMIZATION OF THE SUPERSTRUCTURE

A2.22 Optimization of the superstructure of ships to achieve reduced air and wind resistance has traditionally not been an important subject, as operational effectiveness and building costs have been more in focus. However, for ships with large superstructures and for ships operating at relatively high speeds, there will be a potential for reduction of power consumption by carrying out systematic streamlining of the superstructure to the greatest extent that is possible, such as illustrated in Figure A2.3. Also, wind resistance and drift/rudder resistance may be reduced by modifications to the superstructure (see Figure A2.4).

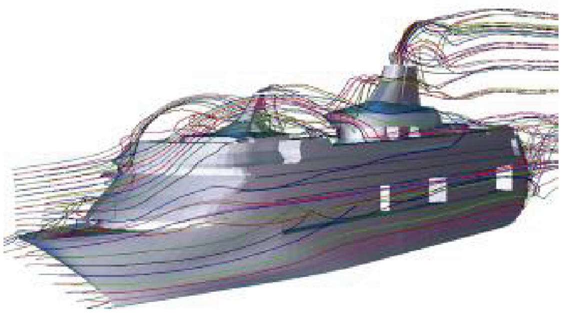


Figure A2.3 *A CFD analysis of wind resistance (CFD Norway)*

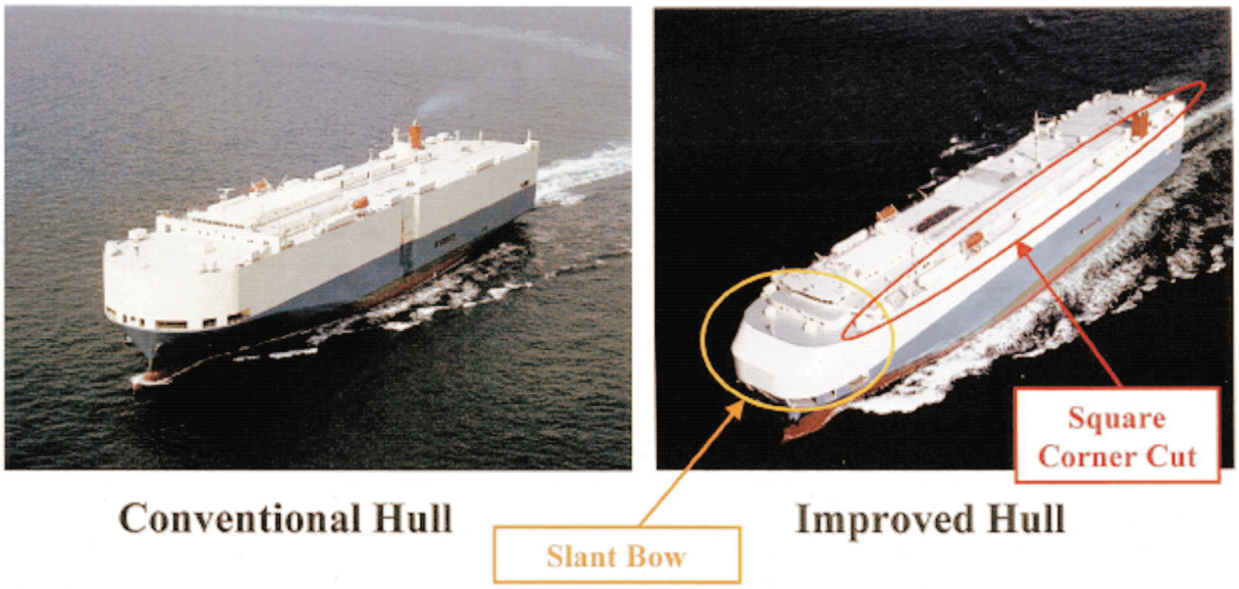


Figure A2.4 *Example of improvements to a superstructure (Universal Shipbuilding)*

RECOVERY OF PROPELLER ENERGY

Introduction

A2.23 A considerable number of devices have been invented for improving the power consumption of ships by recovering as much as possible of this rotational energy in the flow from the propeller, or to provide some pre-rotation of the inflow into the propeller. The most important of these will be considered here.

Coaxial contra-rotating propeller

A2.24 The coaxial contra-rotating propeller is an obvious device for recovering some of the rotational energy. To avoid problems with cavitation, the aft propeller usually has a smaller diameter than the front propeller. The aft propeller is therefore not working on the complete rotating flow field from the forward propeller. In addition, the more complicated shafting results in mechanical losses that offset some of the gain that is obtained by recovering the rotational energy. It is also reported that gearboxes for contra-rotating propellers may present problems. Reported gains in power consumption range from 6% to 20%. Gains of 15% and 16% have been reported from two different full-scale measurements. Contra-rotating propeller arrangements require a short shaft line and are therefore primarily suited to single-screw ships. The arrangement is particularly beneficial for relatively heavily loaded propellers, and the best results (in the form of power consumption) have been found in fast cargo vessels, ro–ro vessels and container vessels. Naturally, this type of technology is tested in cases where it is expected to be particularly suitable. The analysis of losses of rotational energy in paragraphs A2.2 to A2.11 of this chapter suggests that the potential gains that could be obtained with this type of device typically could be around ~3–6%.

Free rotating vane wheel

A2.25 The vane wheel (Grim wheel) is a freely rotating propeller, installed behind the main propeller. The vane wheel has a larger diameter than the main propeller. The part that is directly behind the main propeller is turned by the swirl from that propeller and acts like a turbine, driving the part of the vane wheel that is outside the diameter of the main propeller. This outer part acts as a propeller. Part of the rotational energy is thus transformed into propulsive energy. Improvements in power consumption are reported to be around 10%. It is claimed that an important benefit of the vane wheel is that the smaller main propeller that can then be installed results in a lighter and less costly propulsion unit. The long and slender vane wings may be damaged at sea, especially in a heavy seaway. It should be noted that, if there is space in the after body for a vane wheel, there will also be space for a main propeller of larger diameter, offering approximately the same improvement in power consumption as the combination of a small main propeller and a vane wheel. The vane wheel should be a suitable potential improvement for cargo ships.

Ducted propeller

A2.26 The ducted propeller consists of a propeller mounted centrally in a ring foil. Compared to the conventional propeller of the same diameter and thrust, this arrangement allows a larger mass of water to be supplied to the propeller, improving the operating conditions around the propeller and the ideal efficiency. The duct generates additional thrust. The potential for reduced power consumption on relevant ships has been reported to be in the range 5–20%, with perhaps 10% being a good average value. The duct results in increased resistance, but at higher propeller loadings this is more than compensated for by the positive effects of the combination of propeller and duct. Ducted propellers are therefore suited for ships operating at high propeller loadings, such as tankers, bulk carriers, tugs and different offshore supply and service vessels.

Pre-swirl devices

A2.27 These are devices that aim to provide a favourable pre-rotation of the flow of water in front of the propeller. They include radial reaction fins in front of the propeller and an asymmetric stern. Considering radial reaction fins, a reduction in power consumption has been given as 3–8% from tests with models, while the result that has been reported from a full-scale test was 7–8%. For the asymmetric stern, improvements in power consumption of 1–9% have been reported in tests on models. Radial reaction fins or an asymmetric stern should be applicable to all single-screw ships, and should work according to expectations in many cases. It should be noted, however, that in many cases the expected benefits have not been demonstrated in full-scale operation.

Post-swirl devices

A2.28 A number of devices belong to this category. Several of them involve modifications to the rudder. The most important among these devices may be additional thrusting fins at the rudder, rudder bulb systems with fins, fins on the propeller fairwater (boss cap fins) and an asymmetric rudder. For these devices, gains in power consumption of 1–8% have been reported from tests on models. From full-scale measurements, a gain of 8–9% has been measured for additional thrusting fins at the rudder, while 4% has been reported for boss cap fins. Post-swirl devices should be applicable to all new ships, but, as for pre-swirl devices, the benefits, in many cases, have been difficult to demonstrate in full-scale operations.

Integrated propeller and rudder units

A2.29 As the name implies, the propeller and rudder are designed as an integrated unit, part of the design being a bulb behind the propeller that is fitted into the rudder. At least two patented designs exist. The effect of these units has been reasonably well documented in tests on models and in full-scale trials. An improvement of 5% in power consumption may be taken as typical. The units are applicable to general cargo vessels, RoPax vessels and container vessels operating at relatively high speed.

AFTER-BODY FLOW-CONTROL SYSTEMS

A2.30 After-body flow devices give little improvements in the general case. Still, in the cases of unsuccessful hull designs that lead to after-body flow separation and poor propulsive performance, the flow-smoothing devices can be expected to be of benefit. Such non-optimal designs are more likely to happen when designing ships with full hull forms, especially when the ratio *L*/*B* is small. Flow-smoothing devices are therefore mostly beneficial for tankers and bulk carriers. Two types are presented in the following discussion.

Guide vanes in front of the propeller

A2.31 The aim of guide vanes is to eliminate or reduce the cross-flow that is often observed in front of the propeller. These vanes are fitted in front of the propeller on both sides of the sternpost. The vanes straighten the flow in the boundary layer in front of the propeller, thereby improving its efficiency. Cross-flow appears mostly in ships with stern bulbs and full hull forms that operate at relatively low speed. The benefit is therefore largest for tankers and bulk carriers. The improvement decreases with decreasing fullness of the hull form.

Wake-equalizing duct

A2.32 The wake-equalizing duct consists of one half-ring duct with foil-type sections attached on each side of the after body, in front of the propeller. The half-ring duct accelerates the flow into the propeller in the upper quadrant on each side and retards the flow in the lower quadrants. This results in a more homogeneous wake field in front of the propeller, while the average wake is almost unaltered. The improved power consumption that is obtained from well designed wake-equalizing ducts results from several component savings:

- improved efficiency because of more axial flow and a more homogeneous wake field;
- reduced resistance because of reduced flow separation at the after body;
- lift on the ducts directed forward;
- orientation of duct axes so that the inflow to the propeller is given a small pre-rotation; and
- improved steering, due to straightened flow over the rudder and more lateral area aft.

Alternative propulsion systems

A2.33 The invention and development of external propulsion systems as an improved alternative to the screw propeller, like the development of improved alternatives to the conventional rudder, has a very long history in ship technology. Unlike the field of rudders, where more efficient (but also more complicated and costly) alternatives have been found, the improvements that have been claimed to be obtained from different proposed alternatives to the screw propeller have not been substantiated so far. On some alternatives, involving the design of integrated propeller and rudder units, reduction in power consumption has been measured, but these solutions probably belong under the heading "engine energy recovery" in the next section.

A2.34 The known alternatives go by various names, such as "duck feet", "goose feet", "whale tail" and "fish tail". They all base the development of forward thrust on a more complicated motion than the rotating motion of the propeller. This leads to more complicated mechanical structures that will be costlier to build, costlier to install and costlier to maintain. It is therefore expected that the improvement in power consumption that is required to offset these potential disadvantages needs to be considerable. Even with relatively complicated mechanical structures, the various designs have difficulties replicating the efficient propulsive motion of the members of the animal realm from which they have taken their names. Limited research is still going on in this field, and new results may alter the view given here: however, this is not expected.

ENGINE ENERGY RECOVERY

A2.35 Energy-recovery systems for ship engines have been available from producers of low-speed engines for many years. The first system offered was usually based on an additional exhaust turbine which was fed from the exhaust receiver by a fraction of the engine exhaust flow, in the range of 10%. The exhaust turbine could be connected to the engine's crankshaft or alternatively to an electric generator. Since fuel prices in the past have been too low to make these systems profitable, the number of installed systems is relatively small.

Current situation

A2.36 For some years, more advanced systems have been developed and are today commercial, at least for low-speed engines. An example is B&W's system TES (thermo efficiency system), which combines a turbine in the exhaust gas with a steam cycle that is driven by exhaust heat and running a steam turbine. The two turbines are coupled to a generator for production of electrical power. The power can then be used to drive a shaft generator/motor to assist the main engine, or consumed elsewhere in the ship. The corresponding increase in engine power is estimated to be in the range of 9 to 11%, which, in terms of shaft efficiency, increases to about 55% (from about 49.5%). The contributions from the two systems are respectively 5% and 6%, from the exhaust turbine and the steam turbine. The efficiency of the steam cycle is somewhat limited by the minimum recommended temperature of the exhaust stack, which must be above 180°C to control the formation of deposits and the corrosion by sulphur oxides that are related to the use of heavy fuel oils.

A2.37 Based on a fuel price of US$160 per barrel (in 2004), the payback time has been calculated by the equipment manufacturer to be five years for the largest engines and about 11 years for the smallest engines considered (the range is from 80 MW to 20 MW). A significant barrier to the use of such systems is the very large size, weight and complexity of the installation. Such an installation is optimized for a single operating point, with the power production rapidly decreasing at other loads.

Future possibilities – medium-speed engines

A2.38 Steam cycles, as a means of energy recovery, have some properties that are quite challenging on board a ship. The relatively low temperature level makes systems relatively bulky. In particular, the condenser operates at the low steam density that exists at the actual condensation temperature.

A2.39 There are some interesting forthcoming developments that are expected to make a significant impact on the gain in engine efficiency. Organic Rankine Cycle systems have been designed and are already commercial. They show some favourable properties, in particular much smaller space requirements compared to a steam system. The working fluid is currently alkanes or refrigeration fluids. Due to the properties of the working fluids (fire hazard, ozone-depletion properties), high-pressure CO_2 is considered to be a more desirable working fluid.

A2.40 The medium-speed diesel engines have a lower fuel efficiency compared to low–speed ones, usually in the range 42% to 44.5%. These engines normally have an exhaust gas temperature in the range of 300°C to 360°C. While the minimum temperature of the exhaust stack is 180°C or above, which poses a limitation to heat recovery, the energy utilization is calculated to be in the range of about 3.5% of the shaft power.

Energy recovery from gas-fuelled engines

A2.41 Due to increasing prices of fuel oil and regulations to control exhaust emissions (restricting operations or taxation), there is an increasing interest in using gas engines, burning natural gas, in marine applications. The currently available gas-fuelled engines for ship propulsion, with piston bores in the range of 25 cm to 50 cm, have slightly higher shaft efficiency (at MCR) compared to their diesel counterparts, normally in the range of 44.5% to 47% depending on engine size and engine concept (spark-ignited and dual-fuel). The gas engines offer a higher potential for energy recovery. This comes from the higher exhaust temperatures (normally in the range of 400°C to 430°C) and a possibility to run with an exhaust stack temperature below 100°C. This can be done, while the fuel does not contain any sulphur and the combustion produces very small quantities of particles. Thereby, the exhaust system is likely to be little affected by the low temperature of the exhaust.

A2.42 A simplified calculation, based on an exhaust gas temperature of 430°C and an exhaust stack temperature of 50°C, gives a theoretical (Carnot) efficiency of about 32.5%. Considering a turbine efficiency of 80% and some additional losses related to pumping and heat exchangers, the total recovery efficiency could be in the level of 22%. Using actual figures for exhaust heat flow and engine shaft power, the energy-recovery figure is 13% of the shaft power. That means that the actual shaft efficiency increases from 45% to 50.9%.

Machinery arrangement and hybrid propulsion

A2.43 Currently, tankers, bulk carriers, containerships and general cargo ships have one large low-speed propulsion engine directly connected to the propeller. This arrangement has proven to be very efficient and, since the ships operate mainly at high engine load, there is little to gain by complex multi-engine machinery arrangements or by using hybrid propulsion systems. For the RoPax/cruise segment, it is currently common to use multiple engines and two or more propellers. A primary reason for this is restrictions on draught and high power demand. An additional reason is the space restrictions and the use of medium-speed engines; hence there is already a need (and transmission loss) for a gearbox. This multi-engine situation opens up some possibilities for designing systems that can handle variable loads.

Fuel-cell propulsion

A2.44 Fuel cells have high potential thermal efficiency and low emissions. For this reason, fuel-cell technology is, in principle, also an interesting alternative to the use of traditional combustion engines for merchant shipping. Fuel cells can be used either as standalone or in a combined cycle, where exhaust heat is recovered for additional generation of power. Fuel-cell systems have been identified as particularly promising power generators for both ship hotel power and also for hybrid propulsion systems, where they work in combination with a diesel engine [28]. That said, a small fuel cell has recently been installed as the main propulsion for a small passenger barge [43].

A2.45 There are many issues relating to the use of fuel cells on board ships. Fuel cells use non-conventional fuels, such as hydrogen or methanol, and/or require significant treatment of the fuel. Moreover, there are considerations of price and reliability which make fuel cells presently appear less interesting than other efficiency/abatement options. The main technological obstacles to operating fuel cells on board medium to large ships are their excessive weight and volume as well as the safety of onboard storage and handling of the fuel (hydrogen) [42]. Accordingly, the further R & D priorities include:

- development of fuel processing systems for fuel-cell units capable of running on liquid fuels;
- energy-recovery systems (e.g., boilers, turbines) for use in conjunction/integration with high-temperature fuel-cell systems (MCFC and SOFC);
- standardization of fuel-cell systems (including auxiliary systems) into modules of 0.5 MW to 1.0 MW size;
- intrinsically safe systems for onboard storage of fuel and fuel handling; and
- development and full-scale validation of systems with respect to their use in the marine environment: reliability, availability, vibration, accelerations, salinity, humidity, and ability to respond to transient power demands.

OPERATIONAL IMPROVEMENTS

Fleet composition/selection of ships

A2.46 This relates to newbuildings and also secondhand purchase. Efficiency is dependent on having ships that are suitable for the jobs they do. To this end, efficiency will be increased by concentrating cargo on larger ships. This will reduce the energy consumption of shipping, but the total impact on overall door-to-door logistical performance may be negative unless this move is supported by smaller ships that can assist in the distribution of cargo. Barriers to such development include harbour capacity and facilities for ship-to-ship or other efficient means of transfer of cargo.

Speed reduction

A2.47 Strategic reductions of speed result in more ships being needed; hence, while the power consumption of individual ships is reduced by the third power, the net effect on emissions is a second-power reduction; hence, a reduction of speed by 10% roughly equates to a reduction in shaft power by 27% and an energy saving of 19% on a tonne-mile basis. Reductions in speed are expensive, since they directly affect the freight done and hence the income of a ship. However, when freight rates are low and fuel prices are high, it will be profitable to reduce speed.

A2.48 Speed reductions on existing ships result in sustained operation on low power. This results in a small reduction in thermal efficiency, and may also result in less complete combustion and more deposits being formed within the engine. This is particularly the case for engines with traditional cam-driven fuel pumps, where the injection pressure of the fuel is speed-dependent. Engines with common-rail fuel injection handle low-load operational modes much better.

A2.49 If a shipowner decides to operate at reduced speed on a permanent basis, the engine can be derated. This will then result in better performances and also better fuel economy (although the latter improvement is rather insignificant compared with the gains that are achieved by reduction of speed).

HULL COATINGS

Selection of coatings and strategies for hull maintenance

A2.50 Frictional resistance is a very significant contributor to total resistance, particularly at lower speeds. When the hull moves through the water, water will be dragged along, creating a body of water following the ship that is called a "boundary layer". In the forward part of the ship this layer will be comparatively thin, but it grows in thickness along the sides of the hull. A boundary layer will form even on completely smooth hull surfaces. Increasing the roughness of the hull surface tends to increase the boundary layer, consequently increasing the viscous (frictional) resistance. The effect of surface roughness on the resistance depends on the effective speed of the water relative to the hull, and this varies over the hull surface [17]. Therefore, increased surface roughness in the bow area will cause more additional resistance than, for instance, in the aft areas near the propeller inlet or under the hull bottom.

A2.51 The surface roughness of new ships depend on the quality of manufacture of the wetted plates of the hull (including buckles and welding seams), the type of coating that is used and the quality of application of the coating. The latter refers to achieving a uniform correct thickness and the avoidance of contamination with dust, sand, etc.

A2.52 During operation of the ship, surface roughness can increase due to cracking and damage to the coating as well as to attacks of rust. Additionally, the growth of organic species (including various types of slime and weed fouling as well as acorn barnacles and gooseneck barnacles) can be very detrimental. It should be noted that biological fouling is a very complex process that depends on factors such as the ship's loading condition, its operating zones, the effectiveness of anti-fouling paint and environmental conditions. Furthermore, it predominates in the areas of the hull where there is sunlight, i.e. along the sides of the hull and particularly near the waterline.

A2.53 To counteract organic growth, self-polishing coatings are used. These coatings degrade over time to release substances that inhibit to organic growth. Traditionally, TBT was used; however, currently, inhibitors are copper-based. Biocide-free silicon-based coatings are also available; however, their market share is very small, due to their significantly higher costs. These coatings are commonly referred to as "foul-release coatings" as their working principle is that they have a soft surface onto which it is difficult for most organic foulants (except slime) to hold [30].

A2.54 In a research project managed by MARINTEK, a number of coatings, of both anti-fouling and foul-release type, from five major manufactures have been tested on 16 Norwegian ships over a period of seven years. The results show that these new coatings are equally as effective as TBT-based systems [26]. (TBT-containing paints are banned as a result of the International Convention on the Control of Harmful Anti-fouling Substances on Ships, 2001 established by IMO.)

A2.55 After a period of 3–5 years, the self-polishing coating must be renewed; however, its performance is typically reduced gradually over time, and hence energy consumption may be reduced by having shorter intervals between the application of coatings (which requires dry-docking) and also by brushing the hull. Brushing is typically done by divers, but it may also be done by automated systems. The whole hull or just critical parts can be targeted. Due to the threat of invasive species, many ports have introduced restrictions on brushing. Also, the number of dry docks is limited; hence, if the rapidly growing world fleet would desire to increase its docking frequency, this would be expected to result in a temporary shortage of dry-dock capacity.

A2.56 In order to know at what time it is beneficial to do hull maintenance, the ship operator would need to know the performance of the hull, i.e. the speed obtained in relation to the consumption of power or of fuel. Traditionally, this type of decision is made by fleet management and is based on data reported from the ship. This would typically be "noon reports", giving information on position, speed, fuel consumption and weather. These data are, however, typically not accurate enough to do such analysis. For instance, weather information is only one single observation (for a 24-hour period). Currently, more accurate information is difficult to obtain with sufficient accuracy since the instrumentation that is needed is typically not available on board ships. Additionally, to account for the effect of current it is necessary to measure accurately the speed of the ship relative to water. A GPS-derived speed would be misleading. Obtaining speed through water is a technical challenge in itself, not least due to the flow field that is generated by the ship and the uneven vertical flow profile that can occur in currents. Best-practice performance monitoring today would be to do periodic speed trials, i.e. several runs back and forth in calm waters, although this has not been common practice in recent years.

A2.57 An example of analysis based on data reported from ships is shown in Figure A2.5. This figure shows the correlation between speed gains (at reference power) observed after dry-docking and the speed loss (at reference power) observed before docking. As seen here, the scatter is wide. Lack of accurate data is part of this remedy and variability in the effect of hull cleaning is another.

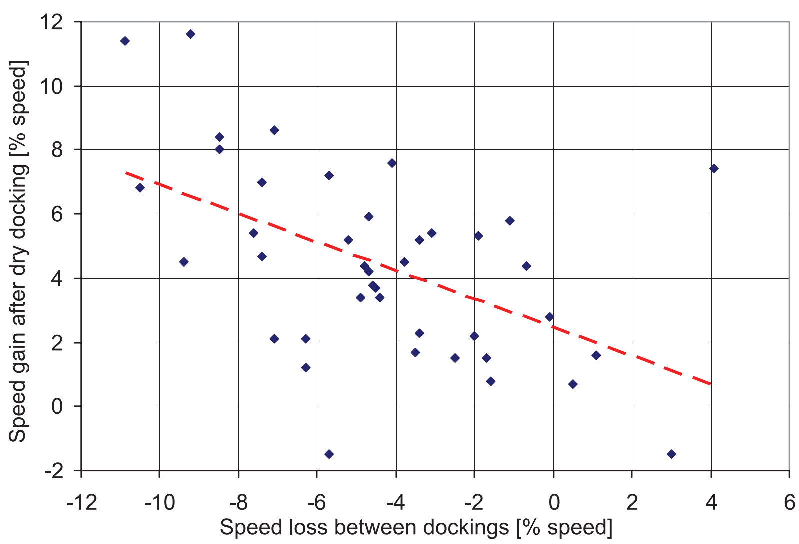


Figure A2.5 *The effect of dry-docking on the speed of a tank ship; the analysis is based on data reported by the ship (primarily, TBT-based self-polishing coatings were used)*

Future coatings and the application of polymers and air lubrication

A2.58 Frictional resistance can be reduced by modifying the wetted surface of the hull, such as by introducing riblets that mimic shark scales or by applying an artificial enhancement (such as the use of air bubbles and/or air cavities and polymers). Research is still going on concerning air lubrication on hull forms for conventional ships, but it has so far not provided significant improvements. Air-lubrication technology is claimed to provide reductions in resistance that are in excess of 5%, which is significant in this context.

A2.59 Adding a small amount of polymer to a turbulent Newtonian fluid flow can result in a reduction of the viscous frictional resistance. During the past three decades, numerous research activities were dedicated to the reduction of frictional resistance by applying polymers. As a result, roughly three main methods of friction reduction by polymers have been developed. The first method is based on a molecular scale, due to the fact that the behaviour of polymer molecules in various model flows has been studied. The second type of method relies on investigation of the effects of polymers on the time-averaged turbulence statistics, while the third type of method examines changes in the coherent turbulent structure due to the presence of polymers. As in the previous case of air-lubrication technology, the three methods of using polymers to reduce frictional resistance are not yet mature, i.e. research in that direction is still going on. Additionally, the concept of continuously injecting polymers into the water may not be suitable for sustainable operation. Therefore, the concept of polymer injection is not considered to be very important for reduction of ship resistance.

A2.60 However, it should be noted that any improvements to the wetted surfaces of the hull that are achieved by these means may also inhibit organic growth. None of the mentioned technologies are proven in service. Additionally, an air-bubble system would require energy to produce the bubbles.

A2.61 Hull coatings based on nanotechnology have been advertised by different companies for some time now, and have also been mentioned in the media recently. It is claimed that these coatings have the potential of reducing the basic viscous frictional resistance of the underwater hull to a considerable extent and to delay the onset of marine growth for an extended period. The claims are largely unsubstantiated at present, but, if they can be even partly realized in the future, power reductions of perhaps 15% may be expected. Thus, this type of coating of the underwater hull will be one of the most important contributions toward reducing fuel consumption and CO_2 emissions for well designed conventional ships. It will be particularly favourable that such coatings probably can be applied both to new ships and to existing ships.

A2.62 In summary, the friction resistance of a hull currently depends on the following parameters:

- Initial roughness, including the application of a coating;
- Robustness of the coating with respect to mechanical damage and biological fouling; and
- Maintenance of the hull;

while barriers to improvement may be classified as:

- Lack of proper monitoring of hull condition/performance;
- Lack of dry-dock capacity (short-term); and
- Port restrictions on hull brushing.

A2.63 Taking into consideration the above discussion, it is likely that, in the future, the viscous frictional resistance will depend on both the ability to reduce the friction of clean hulls and significantly also on the ability to maintain performance over time. Based on MARINTEK experience, the hull fouling of tank ships typically results in speed reductions of ~5% between dockings, corresponding to a power increase of ~15% and an increase in frictional resistance of 20%. By increasing the docking frequency, the average loss could be reduced, resulting in a net power saving of about 5%.

DE-RATING OF ENGINES

A2.64 Historically, de-rating has been used in the past in situations where the standard MCR power is not used, for reasons of fuel savings, where the MCR rating and speed is not utilized. A given engine has a design-related limitation in the peak (maximum) combustion pressure that must not be exceeded in service. The traditional de-rating procedure implies reduction of power combined with advancing the injection timing to restore peak combustion pressure and thereby achieving a certain gain in shaft efficiency. Today, with a focus on reducing NO_x emissions, this method is generally not permissible because this will constitute a "significant modification", as defined in the IMO NO_x Technical Code; hence the de-rating will have to be done taking NO_x emission into account.

A2.65 A modern approach to de-rating is targeting to increase the efficiency while at the same time maintaining or even reducing the NO_x emissions from the engine. Again, a reduction of power output is the key to achieve this measure. The reduction of peak firing pressure that comes from power reduction is restored by increasing the compression ratio and eventually adjusting the ignition timing as a tool to adjust NO_x emission. This method has been proven as successful, particularly on older engines, which are usually built with a low compression ratio and thereby have a significant potential to increase their efficiency.

Example: increase of compression ratio

A2.66 Older engine designs, dating back to 1980's, were commonly built with a compression ratio of 12.5:1. The compression ratios of IMO-compliant engines today normally lie in the bracket between 14.5:1 and 16:1. Taking into consideration a certain power reduction combined with the maximum allowed firing pressure, it is possible to calculate the response in fuel consumption, and even in NO_x emissions, using state-of-the-art engine simulation tools.

A2.67 To demonstrate the efficiency trade-off, an example is calculated below. However, only engine efficiency is considered, using a simplified cycle calculation procedure. The engine in this example has a brake mean effective pressure of 21 bars and a maximum peak firing pressure of 155 bars. Given a planned power reduction to 18 bars BMEP, what will be the gain in efficiency when maintaining the peak firing pressure by increasing the compression ratio? Running the calculation model, the theoretical gain in efficiency is found to be 4.3% when the compression ratio is increased from 12.5:1 to 15:1. In this calculation, the ignition timing has not been changed. Potentially, the NO_x emissions could change as a result of this. Also, an increase in compression ratio from 12.5:1 to 15:1 requires relatively major changes in compression volume at TDC. The solution is usually to produce new pistons (or piston crowns, in the case that the pistons are built up by a skirt and a crown). Therefore, such an upgrade would be quite costly. For most engines, complete engine upgrades, such as outlined below, would be preferred.

ENGINE UPGRADES

A2.68 Engine upgrading is usually motivated by the need to reduce NO_x emissions, to reduce fuel consumption or to increase power output. Upgrade packages are becoming more common as fuel prices are rising and taxes on NO_x emissions are introduced, as is the case in Norway today. Also, IMO's revised MARPOL Annex VI and its provisions for existing engines will create an incentive for engine upgrades. Upgrading packages could offer an extended service life to older engines and business opportunities to engine manufacturers.

A2.69 A typical engine upgrade, targeted at reducing NO_x emissions, must also include components to restore and even reduce the fuel consumption caused by the retarded fuel timing. These components of the upgrade are usually included in an upgrade package:

- new turbocharger or parts for rematching, in order to increase charge air pressure (increase of air flow);
- new pistons or piston crowns, with design modifications to increase compression ratio;
- new fuel pumps or fuel cams to increase injection rate. This is to minimize the loss of combustion efficiency that is caused by the delayed ending of injection resulting from retarding the timing. New fuel nozzles, with increased flow capacity, to match the increase in injection rate; and
- optional parts in such a package could include: a more efficient charge air cooler, new designs of piston ring, new bearing shells for connecting rods and main bearings (improved design/materials).

A2.70 The impact on engine parameters of a well-balanced upgrade package could show results as follows: reduced NO_x emissions (by 20–30%), reduced smoke emissions, reduced CO emissions, reduced SFOC (typically in the range from 0 to 3%); higher figures should be applied to older engines.

A2.71 A barrier to engine upgrades is the significant engineering work in developing the design of the upgrade, the cost of the upgrade and the fact that they are best applied to older engines; these may be installed in older ships, they may have a shorter residual lifetime and they may also be less efficient in other areas.

PROPELLER MAINTENANCE AND UPGRADES

A2.72 Existing ships of the displacement type mostly operate within a moderate Froude number interval (*Fn* ≤ 0.3). This fact dictates the choice of propulsive devices (propellers) that may be used in order to achieve ship thrust. Figure A2.6 shows typical types of propellers that are used on displacement ships.

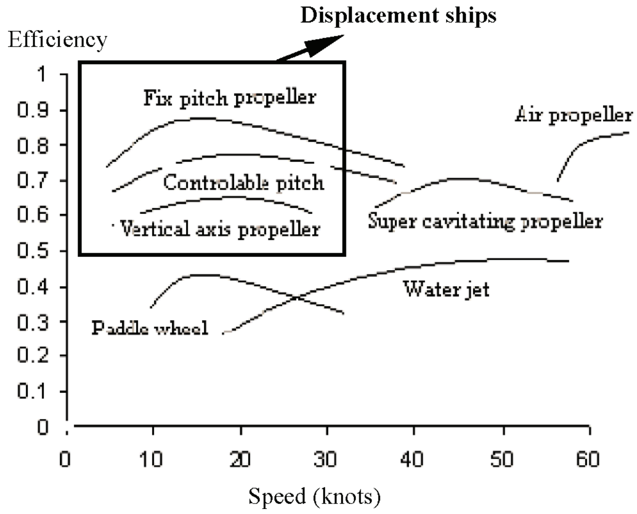


Figure A2.6 *Efficiency of propulsive devices [31]*

A2.73 Classification into three main groups, as shown in Figure A2.6, is adopted in order to illustrate the efficiency of representative propeller groups versus ship speed (in knots). As can be seen from the figure, the most efficient type of propeller is a well-designed fixed-pitch (helical) propeller. However, for other reasons, alternative propulsion devices need to be considered. For instance, controllable-pitch (CP) propellers, although less efficient than fixed-pitched propellers, may be selected if the ship in question needs to satisfy the requirements of rapidly reversing thrust or efficient operation in significantly different environmental conditions. On the other hand, for ships with demands for high manoeuvrability, propellers with a vertical axis may represent a preferable choice. Propeller maintenance and upgrades are options for existing ships, and consist mainly of polishing the propeller, installing a new propeller, and optimizing the pitch of CP propellers.

A2.74 It has been indicated that polishing a roughened propeller surface may result in a decrease in fuel consumption of up to 3%. Polishing will mainly reduce the frictional loss of the propeller but may thereby also reduce the rotational loss. The effect will be greatest for propellers with large area aspect ratios and for propellers running at high rates of rotation.

A2.75 Fitting a completely new propeller to an existing ship has been done in a number of cases, especially when it is expected that there will be improvements in fuel consumption by replacing a propeller with a relatively small diameter that is operating at relatively high RPM with a propeller of larger diameter, operating at lower RPM. Reliable full-scale measurements have not been obtained, but improvements in fuel consumption (up to the order of 15%) have been claimed. This result is probably from a new ship that has an after body that was specially designed for a large-diameter propeller. A more realistic expectation, if a propeller of larger diameter can be installed, may be improvements in the range 5–10% in fuel consumption. Naturally, such upgrades will only be appropriate for a limited subset of ships.

A2.76 A significant barrier to upgrading the propeller is that the shipowner may be unaware of the potential, and there may be problems of documenting performance both before and after the necessary investment has been made.

OTHER UPGRADES

A2.77 There are certain systems that may be improved to reduce energy consumption. This includes speed-control pumps and fans and the substitution of steam with electricity for powering cargo pumps. Some of these upgrades may be profitable; however, the effect of such upgrades on the total energy consumption by the ship is limited.

ALTERNATIVE FUELS AND ENERGY

A2.78 The amount of CO_2 that is emitted from ships depends on the fuel type. For instance, certain fuels may contain more carbon per energy output than other fuels, and hence may produce more CO_2 emissions per unit of work done. The choice of future fuels will depend on a number of factors, such as availability, price, practical suitability for use on board ships, and regulations. Restrictions on the amount of sulphur in fuel are anticipated from the upcoming revised MARPOL Annex VI, as previously discussed.

LIQUEFIED NATURAL GAS

A2.79 Gas that is stored in the liquid state, as liquefied natural gas (LNG), is predicted by many as a forthcoming fuel for ships. Key drivers for this expected development are the low emissions of nitrogen oxides (NO_x), SO_x and particulate matter (PM) from LNG-fuelled ships. Also, LNG contains more hydrogen and less carbon than diesel fuels; hence emissions of CO_2 are reduced. Unfortunately, increased emissions of methane (CH_4) reduce the net effect to about 15% reduction of CO_2 equivalents [21] The price of LNG is significantly less, compared to distillate fuels; therefore there is a considerable economic incentive for a move towards using LNG. The most important technical challenge is finding the necessary space for storage of the fuel on board the ship and the availability of LNG in the bunkering ports. Therefore, LNG is primarily interesting in a regional shipping context, where the ship's range is less of an issue and the next port of bunkering is more predictable. LNG could also become an interesting fuel for tankers, since there is considerable space available for the LNG fuel tanks on deck. LNG-fuelled ships would be particularly attractive in NO_x emission control areas, since they can meet Tier III emission levels without after-treatment of the exhaust gases.

A2.80 LNG-fuelled ships can use either pure gas-fuelled engines or dual-fuel engines that are capable of burning gas, diesel or combinations of these. LNG is a proven technical solution, with 10 ships already in operation and 19 ships on order.

A2.81 Currently, the cost of bulk LNG is about the same as that of residual (heavy) fuel oil, and significantly cheaper than distillate (fossil) fuels. Natural gas can also be processed to produce Fischer–Tropsch diesel, for use in diesel engines; however, in this case, the NO_x benefit that is associated with LNG operation would be lost. Also, natural gas can be reformed on site and used as fuel for fuel cells; however, this is currently not considered to be an interesting option due to the principal fuel-cell challenges (including cost, durability and power density). Presently, only four-stroke medium-speed engines for direct-drive LNG propulsion are already on the market

Biofuels

A2.82 These fuels include current, "first-generation" biofuels made from sugar, starch, vegetable oil or animal fats, using conventional technology. Among these, biodiesel (i.e. Fatty Acid Methyl Esters, FAME) and vegetable oils can readily be used for ship diesel engines. In rough terms, biodiesel could substitute distillate fuels and vegetable oils could substitute residual fuels. With some biofuels, there may be certain issues such as stability during storage, acidity, lack of water-shedding, plugging of fuel filters, wax formation and more which suggest that care must be exercised in selecting the fuel and adapting the engine [22, 23, 24, 25]. Blending bio-derived fuel fractions into diesel or heavy fuel oil is also feasible, from the technical perspective; however, compatibility must be checked, as is also the case with bunker fuels. Future processes to convert biomass into liquid fuels can be designed to synthesize various fuels that are suitable for use on board ships. Currently, biofuels are significantly more expensive than oil-derived fuels [22]. This would have to change if there is to be an incentive to use these fuels on board ships. Moreover, as discussed in the future scenarios, as long as there is a demand, driven by legislation, for biofuels to be used and for carbon reductions on shore, it will be natural to preferentially use biofuels on land, where this is credited, rather than on ships.

WIND POWER

A2.83 Wind power can be utilized in various ways on ships. These include:

- traditional sails;
- solid-wing sails;
- kites; and
- Flettner-type rotors.

A2.84 Although sails were once the only source of propulsion, sails are currently considered to be interesting for providing additional supplementary power, as is suggested by recent studies, for instance [18]. The use of traditional sails will impose bending moments to the hull, causing ships to list. Strength issues could result in a need for masts to run down to the keel, and the presence of the mast and rigging could have significant impacts on cargo handling. Kites differ from other concepts of wind power by having a small footprint during installation and hence being quite feasible to retrofit. Drawbacks with the kite systems include the complex launch, recovery and control systems that are needed. Also, the durability of the lightweight materials that are needed for kite sails is a challenge. Wing sails are solid structures resembling aircraft wings, which provide more thrust with less drag than conventional sails. Flettner-type rotors generate thrust from a rotating object in wind, taking advantage of the so-called Magnus effect. These systems have different characteristics with regards to how the thrust that is generated relates to other parameters, such as wind angle, wind strength, wind stability and ship speed.

A2.85 The energy of the wind varies by region and by area. In a study that was carried out at the Technical University of Berlin [18], three different types of sail were modelled onto two types of ships on three different routes. The objective of that study was to assess the savings of energy and of fuel that might be obtainable over a period of five years, using actual weather data. This study indicated that the potential for sail energy was better in the North Atlantic and North Pacific as compared to the South Pacific. Fuel savings were slightly larger at higher speeds; however, in terms of percentages; the fuel savings were greater at low speed due to the low total demand for propulsion power. In percentage terms, savings were typically about 5% at 15 knots, rising to about 20% at 10 knots. With optimal weather routeing, these figures improved. The best ship with the best sail type, with optimal weather routeing, operating in the most favourable five-year average weather (North Atlantic), was shown to save 15% at 15 knots and 44% at 10 knots. Presently, full-scale trials are being undertaken using kites. This technology is also discussed, in the context of marginal cost and abatement potential, in Appendix 4.

A2.86 Naturally, it is difficult to simulate such complex systems, and currently there is limited full-scale experience with modern commercial sail ships against which such a model can be validated. Also, without such experience, it is also difficult to assess the practical feasibility of the size and number of sails modelled. The above figures should thus be considered indicative. Nevertheless, sail-assisted power does seem to be an interesting opportunity for saving fuel in the medium- and long-term picture.

SOLAR POWER

A2.87 When assessing the potential of solar power for application on ships, it is interesting to consider the potential available energy. Earth's average solar irradiance on the surface is approximately 342 W/m^2 [7]. On average, 30% of this radiation will be reflected back to space [8]. Clouds are the main contributor to the reflection. The solar irradiance will vary with latitude, season, weather conditions and time of day. How much of this energy a photovoltaic cell will be able to capture depends on the efficiency of the cell and the positioning of the cell relative to the solar beam. Current solar cells have an efficiency of about 13% [10]. Today, the best technology, which is used in laboratories and on spacecraft, has an efficiency of approximately 30% [9]. Efficiencies are predicted to reach 45–60% when third-generation photovoltaic cells are developed and matured [9]. The specific power of solar cells is given in Table A2.3.

Table A2.3 *Indicative specific power of solar cells*

	Current	Current best	Future
Approximate energy conversion efficiency (%)	13	30	60
Nominal power (W/m^2)	44	103	205
Power adjusted for reflection (W/m^2)	31	72	144

A2.88 To get an idea of how much power it is possible to get from photovoltaic cells on a ship, the following example calculation has been made for a tanker with a length of 270 m and a breadth of 50 m (see Table A2.4). A tanker of this size is equipped with an engine that is rated to approximately 18,000 kW, and the auxiliary power would be around 1,000 kW.

Table A2.4 *Power production by photovoltaic cells, assuming that the tanker's deck area is completely covered by solar cells*

	Current	Current best	Future
Approximate energy conversion efficiency (%)	13	30	60
Nominal power (kW)	609	1,406	2,811
Power adjusted for reflection (kW)	426	984	1968

A2.89 Current solar-cell technology would thus, on average, only be sufficient to cover a fraction of the auxiliary power even if the complete deck area was covered by photovoltaic cells. Therefore, it can be concluded that, due to the limited capacity of solar cells in respect to surface area that they cover, they do not yet appear to be a very efficient source of energy supply. Furthermore, at certain times and in certain areas, solar radiation will be above average and the auxiliary power demand could be met. Also, by using highly efficient (presumably expensive) spacecraft-type solar cells, current power demand could, on average, be met.

A2.90 Also, since solar power is not always available (e.g., at night) backup power would be needed; even if the power is available, on average, at day time, this would not help reduce the demand for auxiliary power at night unless there is an energy storage system available on board.

A2.91 Solar energy can also be used for heating purposes, e.g., of water while the ship is in port. (Excess heat is normally available on board ships at sea.)

A2.92 Currently, it would appear that solar cells are not very attractive for covering large maritime power demands; however, in a long-term perspective, they could very well be interesting as a partial source of the power that is needed, especially if combined with (or even integrated into) sails.

Wave power

A2.93 This includes concepts for utilizing wave energy and/or ship motion. Examples include internal systems (gyro-based) within the ship and external systems such as wavefoils, stern flaps or the use of relative movement between multiple hulls (trimaran). These systems have high technical complexity, limited potential and generally small interest, and are not considered further here.

EMISSION-REDUCTION OPTIONS FOR OTHER RELEVANT SUBSTANCES

A2.94 This section briefly discusses emission-reduction options for NO_x, SO_x, PM, CO and NMVOC.

Emission-reduction options for NO_x

A2.95 Nitrogen oxides (NO_x) are formed in the engine, mainly as a result of reactions between nitrogen and oxygen from the combustion air. The formation of NO_x is mainly dependent on the combustion temperature and the detention time at high temperatures. Some of the NO_x that is formed is also related to the nitrogen that is in heavy fuel oil, although this is a small fraction.

A2.96 Key strategies for reducing NO_x in the engine involve reducing peak temperatures, reducing the time for which gases are at high temperatures and reducing the concentration of oxygen in the charge air. This can be achieved through a range of approaches (Figure A2.7).

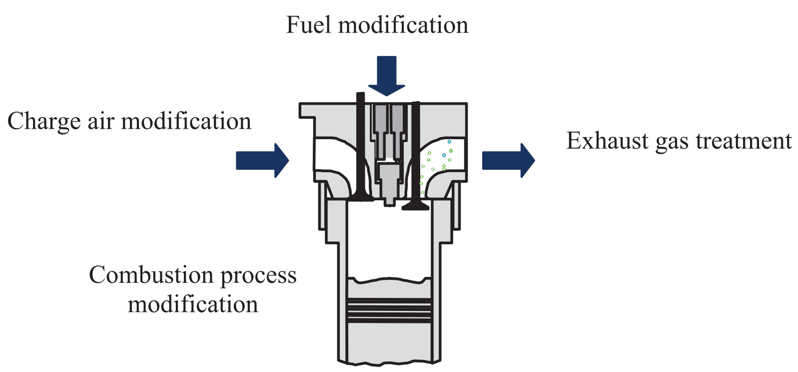


Figure A2.7 *Approximate efficiency of propulsive devices [31]*

A2.97 Fuel modifications include using a water–fuel emulsion, the use of fuels that have a lower nitrogen content and using fuels with different combustion properties that enable different optimization of the engine. Water–fuel emulsions have limited potential to reduce NO_x emissions (~20%) [10] and may result in lower maximum power output. The deposit-forming tendency of a fuel influences the possibilities for other emission-reduction technologies, such as exhaust gas recirculation (EGR) or selective catalytic reduction (SCR).

A2.98 Possible modifications of the charge air include its humidification (sometimes referred to by trade names such as “HAM” or “SAM”) and a reduction in oxygen content through EGR or by the use of air intake membranes to reduce the partial pressure of oxygen in the charge air. In the latter case, the engine intake air is sucked through a membrane, which results in a lower O_2 content in the intake air and lower formation of NO_x. This does, however, result in a reduction in the thermal efficiency of the engine. Sea trials with membrane technology in a sub-optimal retrofit installation revealed reductions of only 6% [3]. The potential for EGR is limited, due to the fouling of the engine that occurs with present-day marine fuels. The consumption and the purity of water are issues with wet technologies. Potential reductions that can be achieved by these technologies are about 40–70%, depending on the type of modification and the engine [10].

A2.99 Modifications of the combustion process include adjusting fuel injection rate, timing, compression ratio, etc., to minimize the creation of NO_x. Examples include the use of Miller cycles to reduce charge temperature and direct injection of water into the cylinders. A certain trade-off exists, as emissions of CO_2 and of PM increase when emissions of NO_x are reduced. This does not mean that future engines, with lower NO_x levels, must have higher CO_2, HC, CO and PM emission levels than current models. Simultaneous improvement in several areas is possible, as demonstrated in [1]. What remains is that, if the improved engine was re-optimized, NO_x could still be traded against other pollutants. Miller cycling in combination with two-stage turbocharging has resulted in reductions of NO_x of >40% and improved fuel consumption in four-stroke engines [1].

A2.100 The use of LNG as a fuel is both a switching of fuel and a change in the combustion process. LNG operation can bring about very large reductions in NO_x (~90%) in four-stroke engines [21]. The potential to reduce NO_x emissions for large two-stroke engines has not been demonstrated. Use of LNG as a fuel is discussed in Chapter 5 in the context of reduction of emissions of CO_2.

A2.101 At present, treatment of the exhaust gas to reduce NO_x emissions exclusively uses selective catalytic reduction (SCR), where urea (or, in certain cases, ammonia) is used with a catalyst to convert NO_x to nitrogen. Other post-treatment technologies have been proposed, including NO_x scrubbing and NO_x adsorption traps. The potential for NO_x scrubbing on board ships is limited by the nitrogen limitation of the IMO scrubber effluent guidelines [41]. Adsorption of NO_x is limited, *inter alia*, by fuel sensitivity.

A2.102 Tier II NO_x limits, i.e. 15–20% reduction from current levels, can be achieved with modifications of the process of internal combustion.

A2.103 At present, Tier III NO_x reduction limits (~80% reduction from Tier I) can only be achieved by selective catalytic reduction (SCR) post-treatment or by using LNG and lean premixed combustion. These technologies are proven for four-stroke engines; however, experience with large two-stroke engines is limited. However, engine manufacturers are pushing the limits of NO_x reduction through various dry and wet combinations of charge air and modifications of the combustion process. It is not impossible that some engines may be certified to Tier III by using other solutions.

A2.104 Using SCR and LNG technology, it is possible to achieve reductions of emissions even beyond Tier III limits on some load points. However, achieving further reductions at low load is problematic with SCR, principally because the temperature of the exhaust gas of marine engines is not sufficiently high for effective operation of the catalyst. Achieving reduction of emissions consistently to a very low level for extended time periods may prove problematic with a catalyst, due to its possible deactivation. Technology for reduction of NO_x emissions at low load in marine engines is presently being forced by IMO through the requirements of the modified Tier III test cycle in the revised NO_x Technical Code.

Emission-reduction options for SO_x

A2.105 Emissions of SO_x originate in the sulphur that is chemically bound to the hydrocarbon fuel. When the fuel is burned, the sulphur is oxidized to SO_x (mainly SO_2). In order to reduce SO_x emissions, it is necessary to use a fuel with lower sulphur content or to remove the SO_x that is formed in the combustion process. The revised MARPOL Annex VI ensures significant SO_x reductions through limitations on the sulphur content of fuels.

A2.106 As an alternative to using low-sulphur fuels, an exhaust gas-scrubbing system can be employed to reduce the level of sulphur dioxide (SO_2). Two main principles exist: open-loop seawater scrubbers and closed-loop scrubbers. Both systems rely on contacting the exhaust with water Open-loop scrubbers use seawater directly, while closed-loop scrubbers use water with chemicals added to provide ability to remove SO_2. Both scrubber concepts may also remove PM and limited amounts of NO_x [8, 9]. Scrubber technologies require energy, which is estimated to be in the range of 1% to 2% of the MCR [10]. Scrubbing to remove SO_x reduces the temperature of the exhaust gas. On the other hand, SCR technology requires high temperatures of the exhaust gas and at the same time low sulphur and PM content in that gas.

A2.107 Pollutant material that is removed from the exhaust is carried in the washwater. SO_x react with the seawater to form stable compounds that are abundant in seawater and not believed to pose danger to the environment. On the other hand, any particulate matter in the exhaust that is trapped in the seawater may be harmful to the environment. The revised IMO Scrubber Guidelines [41] provide limits for the effluent, including limits for Polycyclic Aromatic Hydrocarbons (PAH), turbidity, pH, nitrates and other substances. Port State requirements for effluent discharges will have a significant impact on the possible use of seawater scrubbers. To fulfil these requirements, it will be necessary to install a treatment system to clean the effluent. Generally, the more SO_x and PM that is removed from the exhaust by the scrubber, the more pollutant will have to be removed from the effluent.

Emission-reduction options for PM

A2.108 Unlike other emissions, which are chemically defined, particulate matter (PM) is traditionally defined as the mass that is collected on a filter under specified conditions. Particle growth is a complex process that starts during combustion but continues through the exhaust pipe and in the atmosphere. Therefore, the sampling conditions are critical to the results that are obtained. The chemical composition and the size distribution may also be very different before and after a reduction measure has been applied. Therefore, although very significant improvements may be obtained in terms of PM mass, the benefit in terms of public health may be less significant.

A2.109 As also discussed in Chapter 7, particulate matter consists of:

1. Organic Material (OM);
2. Elemental Carbon (EC);

3. Sulphate (SO_4) and associated water; and
4. Ash.

A2.110 Organic material is related to the consumption of engine lubricating oil, which may potentially be reduced. Changes in lube oil additives may also reduce the PM mass. Emissions of elemental carbon are related to the soot that is formed during combustion, some of which may be removed. Organic material and elemental carbon may therefore be considered to be fuel-independent. Sulphate, associated water and ash are mainly determined by the fuel. When the sulphur content of the fuel is high, the PM emissions are mainly fuel-dependent, while other PM fractions are comparatively insignificant. When the sulphur content of the fuel is reduced, fuel-independent PM is less prominent.

A2.111 Some PM emissions from high-sulphur fuels can be reduced by scrubbing exhaust gases with seawater. Claims for the potential reduction of PM range from 90% to 20%, depending on the source [9, 10]. With low-sulphur fuels, PM emissions can be further reduced by optimizing combustion for increased oxidation of soot and of PM, minimizing the consumption of lube oil and minimizing the use of lube oil additives. Using fuel-water emulsions instead of pure fuel can also reduce PM emissions to a certain extent.

A2.112 Post-treatment technologies that have been considered or used in the automotive sector, such as Non-Thermal Plasma, particulate traps and oxidation catalysts, are not regarded as being suitable for marine fuels; even future SECA levels of 0.1% are insufficient [10].

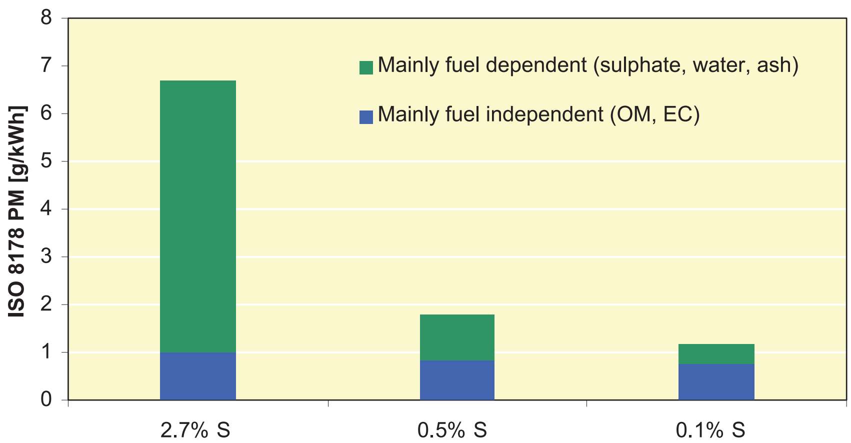


Figure A2.8 *The influence of fuel on PM mass. Data: GL [7]*

Emission-reduction options for CH4 and NMVOC

A2.113 Emissions of methane (CH_4) and NMVOC in engine exhaust are comparatively low. Some reductions may be achieved by optimizing the combustion process. NMVOC may also be oxidized with a catalyst. Oxidation catalysts are not uncommon in conjunction with SCR installations, where they oxidize unused ammonia, thus eliminating emissions of ammonia. Emissions of CH_4 are more difficult to reduce by using a catalyst.

A2.114 Emissions of CH_4 from gas-fuelled engines are due to unburned methane from the premixed combustion process. The level of CH_4 emissions depends on the layout of the combustion chamber. By careful design to avoid crevices, emissions can be significantly reduced. However, there will be a remaining level of CH_4 emissions. This CH_4 can be oxidized by using a catalyst, although this is not as simple as reducing NMVOC, and this is an area for research and development.

A2.115 Methane emissions from gas-fuelled engines can be virtually eliminated by replacing the lean premixed combustion concept with high-pressure gas injection. This latter concept is believed to be beneficial for large two-stroke engines. The disadvantage of this option is that the reduction of NO_x that can be achieved through direct injection is less than can be achieved with lean premixed combustion.

REFERENCES

1 Nicholls, C. 2008. "Unsettled waters ahead for shipping". *Naval Architect*, June 2008: 93–97. ISSN 0306-0209.
2 BIMCO/ISF Manpower 2005 Update The worldwide demand for and supply of seafarers, BIMCO 2005 http://www.marisec.org/resources/manpower2005update.htm
3 Forum for emissions reduction in ships, Norwegian Ship Owners Association, 2007.
4 UNCTAD. Review of maritime transport, 2007.
5 Presentation by Kjeld Aaboe. MAN B&W.
6 Alert! The International Maritime Human Element Bulletin, issue 16, January 2008. ISSN 1747-5007. http://www.he-alert.org/documents/bulletin/Alert!_16.pdf
7 Wikipedia http://en.wikipedia.org/wiki/Solar_radiation
8 Twidell, J. and Weir, T. 2005. *Renewable energy resources*. Taylor & Francis, Abingdon, UK. ISBN 978-0-419-25320-4.
9 Green, M.A. 2002. "Third generation photovoltaics: Solar cells for 2020 and beyond". *Physica E*, 14, 65–70.
10 Solar module REC Solar SCM 210 Datasheet. http://www.recgroup.com/default.asp?FILE=items/2225/393/
11 Sakamoto, T. and Baba, E. 1986. "Minimization of resistance of slowly moving full hull forms in short waves". In Proceedings of the 16th Symposium on Naval Hydrodynamics, Berkeley, USA, 13–18 July 1986, pp. 598–612.
12 Faltinsen, O.M., Minsaas, K., Liapis, N. and Skjørdal, S.O. 1980. "Prediction of resistance and propulsion of a ship in a seaway". In Proceedings of the 13th Symposium on Naval Hydrodynamics, Tokyo, Japan, 1980, pp. 505–529.
13 Ueno, M., Nimura, T., Miyazaki, H. and Nonaka, K. 2001. "On steady horizontal forces and moment due to short waves acting on ships in manoeuvring motion". In Proceedings of the 8th International Symposium on Practical Design of Ships and Other Floating Structures, Shangai, China, 2001, pp. 671–677.
14 Matsumoto, K., Naito, S., Takagi, K., Hirota, K. and Takagishi, K. 1998. "BEAK-BOW to reduce the wave added resistance at sea". In Proceedings of the 7th International Symposium on Practical Design of Ships and Mobile Units, The Hague, The Netherlands, 1998, pp. 527–533.
15 Fujii, H. and Takahashi, T. 1975. "Experimental study on the resistance increase of a ship in regular oblique waves". In Proceedings of the 14th ITTC, Vol. 4. Ottawa, Canada, 1975, pp. 351–360.
16 Nakamura, S. and Naito, S. 1977. "Propulsive performance of a container ship in waves". *Journal of the Society of Naval Architects of Japan*, 15(1): 24–48.
17 Faltinsen, O.M. 2005. *Hydrodynamics of High-Speed Marine Vehicles*, Cambridge University Press, Cambridge, UK.
18 Clauss, G.F., Siekmann, H. and Tampier B., G. 2007. "Simulation of the operation of wind-assisted cargo ships". 102 Hauptversammlung der Schiffbautechnischen Gesellshaft, 21–23 November 2007, Berlin.
19 Davies, G.O. and Freese, R.G. 1981. "The preparation and performance of coal derived diesel fuel", Proceedings of the 14th International Congress on Combustion Engines, Diesel Engines, Helsinki, Finland, 1981.
20 Vallentin, D. 2008. "Driving forces and barriers in the development and implementation of coal-to-liquids (CtL) technologies in Germany". *Energy Policy*, 36: 2030–2043.
21 Einang, P.M. 2007. "Gas-fuelled ships" CIMAC paper 261; Proceedings of the 25th CIMAC World Congress on Combustion Engine Technology, Wien, Austria, 21–24 May 2007.
22 Opdal, O.A. and Fjell Hojem, J. 2007. "Biofuels in ships: A project report and feasibility study into the use of biofuels in the Norwegian domestic fleet", ZERO report 18 December 2007.
23 Ollus, R and Juoperi, K. 2007. "Alternative fuels experiences for medium-speed diesel engines". CIMAC paper 234; Proceedings of the 25th CIMAC World Congress on Combustion Engine Technology, Wien, Austria, 21–24 May 2007.
24 Matsuzaki, S. 2004. "The application of the waste oil as a bio-fuel in a high-speed diesel engine". Proceedings of the 24th CIMAC World Congress on Combustion Engine Technology, Kyoto, Japan, 7–11 June 2004.
25 Ohgawara, T., Okada, H., Tsukamoto, T., Iwasawa, K. and Ohe, K. 2007. "Application study of waste-vegetable oils as a bio-fuel for diesel engine by high-density cavitation". CIMAC paper 196; Proceedings of the 25th CIMAC World Congress on Combustion Engine Technology, Wien, Austria, 21–24 May 2007.
26 Vold, K.H. 2008. Green Efforts on Existing Ships: Test Programme for TBT-free Anti-fouling Paints, Final Summary report March 2008; 16 dry dock reports. Signature: Rev-2, 27 March 2008.
27 Ocean Policy Research Foundation. 2008. "The World's Changing Maritime Industry and a Vision for Japan" http://www.sof.or.jp/en/topics/08_04.php
28 Townsin, R.L. 2003. "The ship hull fouling penalty". *Biofouling*, 19(1): 9–15.
29 Rawson, K.J. and Tupper, E.C. 2001. *Basic Ship Theory*, Vol. 1 and 2. Butterworth–Heinemann, Oxford, UK.
30 Skejic, R. and Faltinsen, O.M. 2008. "A unified seakeeping and maneuvering analysis of ships in regular waves". *Journal of Marine Science and Technology*, 13: 371–394, doi:10.1007/s00773-008-0025-2, http://www.springerlink.com/content/88373xm3g12h4067/fulltext.pdf
31 Wik, C. and Hallback, B. 2007. "Utilisation of 2-stage turbo charging as an emission reduction means on a Wärtsilä 4-stroke medium-speed diesel engine". CIMAC paper 101; Proceedings of the 25th CIMAC World Congress on Combustion Engine Technology, Wien, Austria, 21–24 May 2007.
32 Einang, P.M. 2007. "Gas-fuelled ships" CIMAC paper 261; Proceedings of the 25th CIMAC World Congress on Combustion Engine Technology, Wien, Austria, 21–24 May 2007.
33 Bergh, O. NO_x verifikasjon. B/F "TRESFJORD" MARINTEK report MT28 F06–010.
34 Maeda, K., Takasaki, K., Masuda, K., Tsuda, M. and Yasunari, M. 2004. "Measurement of PM emission from

marine diesel engines". CIMAC paper 107; Proceedings of the 24th CIMAC World Congress on Combustion Engine Technology, Kyoto, Japan, 7–11 June 2004.
35 Okada, S., Senda, J., Tsujimoto, K. and Kitagawa, K. 2007. "Physical characteristics of particulate matter emission from medium-speed marine diesel engine". CIMAC paper 59; Proceedings of the 25th CIMAC World Congress on Combustion Engine Technology, Wien, Austria, 21–24 May 2007.
36 Wall, J.C. and Hoekman, S.K. 1984. "Fuel composition effects on heavy-duty diesel particulate emission", SAE Technical paper series 841364.
37 Kurok, C., Pawils, V., Brumm, H. and Götze, H.J. 2007. "Emission of particulate matter from marine diesel engines", presentation at IMO BLG WGAP2, Berlin, 2007.
38 Ives, R. and Klokk, S. 1993. "Exhaust gas sulphur removal by sea water washing, marine diesel engines". Paper D58; Proceedings of the 20th CIMAC World Congress on Combustion Engines, London, UK, 17–20 May 1993.
39 Bak, F. 2007. "The influence of a SO_x abatement plant on diesel engine emissions". CIMAC paper 99; Proceedings of the 25th CIMAC World Congress on Combustion Engine Technology, Wien, Austria, 21–24 May 2007.
40 CIMAC. 2008. "Guide to diesel exhaust emissions control of NO_x, SO_x, particulates, smoke and CO_2 – seagoing ships and large stationary diesel power plants, 2008". CIMAC Recommendation 28.
41 IMO. 2008. "Guidelines for exhaust gas cleaning systems". IMO resolution MEPC.170(57) http://www.imo.org/includes/blastDataOnly.asp/data_id%3D22480/170%2857%29.pdf
42 EU project G3RD-CT-2002–00823. FCSHIP – Fuel Cell Technology for Ships – Synthesis of open problems and Roadmap for future R&D, June 2004.
43 Mertens, A. "Fuel Cell Systems for Zero Emission Ships: the Zemships Propulsion System and beyond". Presented at Zemships conference, H2 Expo, Hamburg, Germany, 22 October 2008 http://www.zemships.eu/de/DateienDownloadbereich/Conference/P6_Zemships_conference.pdf

Appendix 3

Calculation of energy distribution on board ships

INTRODUCTION

A3.1 This appendix presents the calculation of energy distribution on board ships that is described in Appendix 2. The method gives estimates of energy consumption by using the prediction of different loss components of displacement ships when sailing in calm water and (head) weather conditions. Results are given for ten different ships at service speed and at reduced speed. The ten ships that were selected include one tanker, one ultra-large ore carrier, two containerships, three ro–ro ships, one chemical carrier and two cargo ships. The model builds on work done by MARINTEK that was presented in AEA (2008).

A3.2 The present model expands the previous one by including estimation of the additional power allowance due to weather (irregular wave field and wind) by using a recently published, approximate method that has been formulated by Kwon (2008). The method, as will be shown in the following discussion, is capable of predicting the involuntary reduction in speed and, consequently, the additional power allowance with accuracy within the engineering practice for a general type of ship which operates in generalized weather conditions.

Decomposition of total resistance R_T for displacement ships

A3.3 The total resistance R_T for a displacement type of ship is decomposed according to Figure A3.1. The decomposition consists of two main components, namely total resistance in calm water R_{TCW} (Larsson and Baba, 1996) and total added resistance R_{TADD}, which is further decomposed into added resistance due to current R_{AC}, different (two) fluid layers R_{AL}, ice loading R_{AIce}, waves R_{AW} and wind R_{AWN}. The first three components of added resistance (current, fluid layers and ice) are not accounted for in the present study. This is because the ship, during its operational lifetime, mostly experiences loading due to weather effects associated with the short-wavelength irregular waves and wind (Faltinsen, 2005). Consequently, this means that the additional loadings due to current, fluid layers and ice are considered here to be of local exceptional importance.

A3.4 The evaluation of the ship's total calm-water resistance R_{TCW} can be performed by several different methods. According to Carlton (1994), these are classified in four basic classes of methods: the direct model test, the traditional and standard series methods, the regression-based methods and the computational fluid dynamics (CFD) methods. Since the present study requires the optimal accuracy of the total calm-water resistance R_{TCW}, the regression analysis methods, which are based on results from direct model tests (MARINTEK's 2008 database of results from performance tests), are chosen as an efficient approach for the prediction of this quantity. However, it should be noted that, although the computational fluid dynamics-based methods give higher accuracy than the traditional and standard series or regression analysis methods, they are excluded simply because their application is too complex from the perspective and goal of the present study.

A3.5 The traditional and standard series methods have similarity with the regression analysis methods, i.e. both methods only need a few global ship design parameters (block coefficient C_B, prismatic coefficient C_P, . . .) to predict the ship's total resistance in calm water. However, they are not selected because of their limited accuracy in the estimation of the total calm-water resistance for the modern ship hull forms. The additional detailed discussion related to the above-mentioned methods can be found in Carlton (1994), Schneekluth and Bertram (1998) and Bertram (2000).

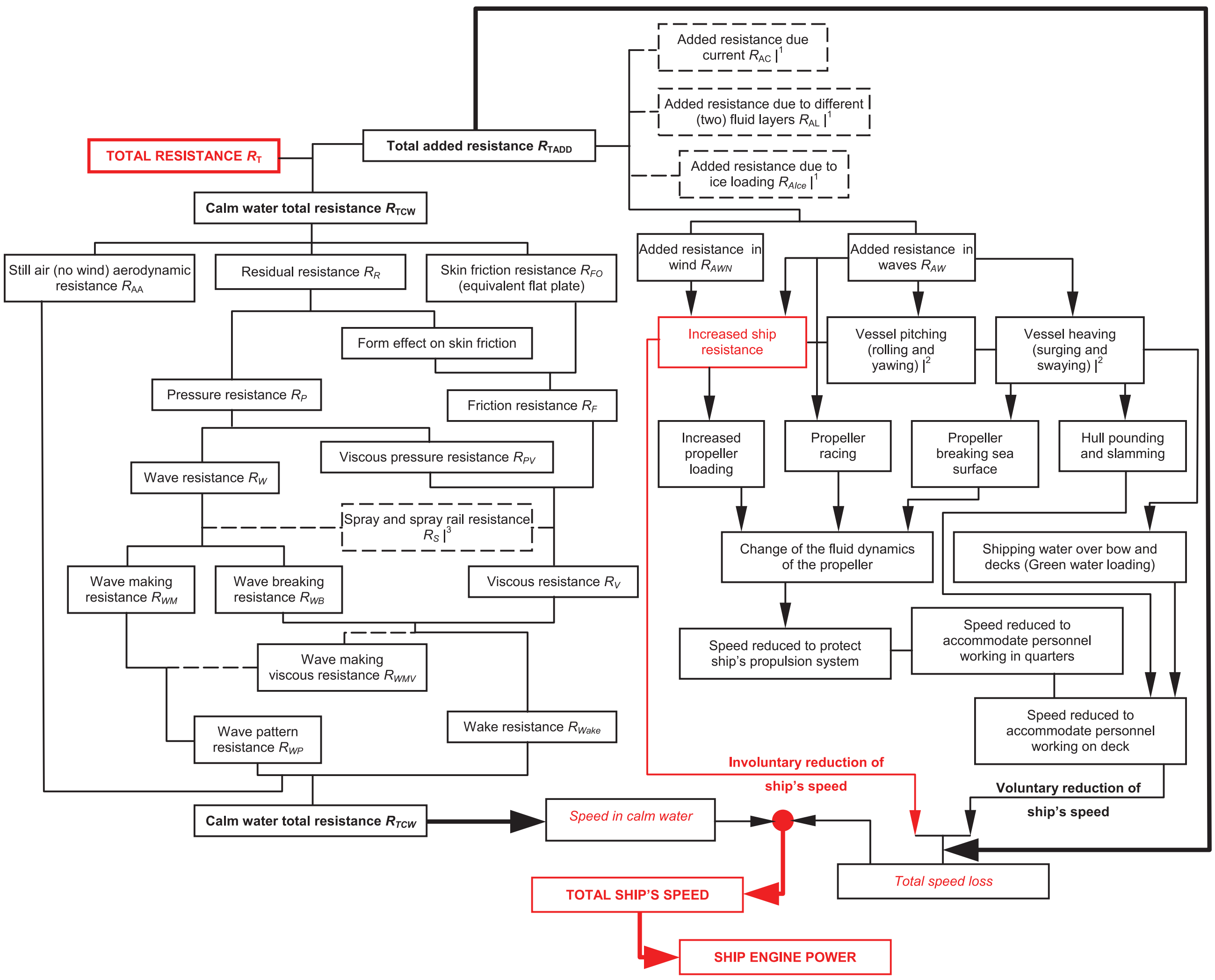


Figure A3.1 The decomposition of total resistance R_T and effects due to waves and wind loading on displacement type of ships.

Note: |[1] Added resistance due to current R_{AC}, different (two) fluid layers R_{AL} and ice R_{AIce} is not accounted for in the estimation of involuntary speed loss that is presented later in this study. |[2] When a (displacement) ship executes manoeuvres in waves, all modes of ship motions contribute to the evaluation of added resistance in waves R_{AW}. |[3] Spray and spray rail resistance R_S have negligible effect. The reason is that a displacement ship usually operates up to Froude number $Fn <\approx 0.25$, which is significantly below Froude number Fn 0.5, when the two mentioned components of the resistance start to show contributing effect to calm water total resistance R_{TCW} (Faltinsen, 2005).

DIRECT MODEL TESTS IN CALM WATER CONDITIONS

A3.6 MARINTEK's 2008 database of the results of direct model tests is used to establish the components of the propulsion loss that is associated with the calm water conditions. First, they are obtained in coefficient form and then transformed to the ship scale for each particular group of ships (four in total) mentioned previously. The following coefficients have been used for the present purpose:

- Calm water total resistance: C_{TCW};
- Friction resistance: C_F;
- Residual resistance or wave resistance: C_W; and
- (Still) Air resistance: C_{AA}.

A3.7 From the propulsion tests, the following results have been used:

- Mechanical efficiency: η_M;
- Quasi-propulsive coefficient: η_D; and
- Wake fraction: w.

A3.8 A set of calculation procedures is carried out in order to arrive at the estimation of components of the propulsion loss. They are outlined as follows.

Calculation of resistance components

A3.9 Resistance components are predicted according to the following expressions:

1. Wave resistance R_W: $R_W = C_W \cdot \frac{\rho_S}{2} \cdot V_S^2 \cdot S_S$ (N);
2. (Still) Air resistance R_{AA}: $R_{AA} = C_{AA} \cdot \frac{\rho_S}{2} \cdot V_S^2 \cdot S_S$ (N);
3. Friction resistance R_F: $R_F = C_F \cdot \frac{\rho_S}{2} \cdot V_S^2 \cdot S_S$ (N); and
4. Eddy-making resistance $= (C_T - C_R - C_{AA} - C_F) \cdot \frac{\rho_S}{2} V_S^2 \cdot S_S$ (N),

where:

S_S = wetted surface area of the hull (m^2)

V_S = ship speed (m/s). Note: 1 knot = 0.514 444 4 m/s

ρ_S = mass density of seawater; ρ_S = 1,025.0 kg/m^3.

The relative loss components are then found by calculating the resistance components above as fractions of the total calm-water resistance R_{TCW}.

A3.10 The viscous resistance, R_V, which is the sum of the friction resistance and the eddy-making resistance, will be almost independent of ship speed V_S in the speed region that the ship has been designed for.

A3.11 The method above means that a simplification has been made. The transom stern resistance, the appendage resistance, as well as the effect of the form factor have been lumped together with the viscous resistance and finally with the eddy-making resistance. This should be sufficiently accurate for the present purpose.

CALCULATION OF PROPELLER LOSS COMPONENTS

A3.12 The propulsive loss connected to the efficiency of the propeller when operating behind the hull is expressed by $1 - \eta_D$, where η_D is the quasi-propulsive coefficient, which is determined by the propeller's open-water efficiency η_O found in tests in open water, and the relative rotative efficiency η_R, and the hull efficiency η_H. The two latter coefficients are determined in propulsion tests.

A3.13 The total loss due to the propeller and propeller–hull interactions, expressed by $1 - \eta_D$, has been divided into the components:

- axial loss;
- friction loss; and
- rotational loss.

Only the total loss, expressed by $1 - \eta_D$, can be and has been extracted directly from the results from propulsion tests. The mechanical efficiency coefficient for individual ship projects is information that is provided by the designer of the ship. The other loss components that are described above require some calculations in order to obtain their quantitative values.

Mechanical efficiency coefficient

A3.14 The mechanical efficiency coefficient η_M is provided by the designer of the ship, and the value is generally in the range 0.96–0.98 for ships with normal arrangements of the propeller shaft (Carlton, 1994). In the adopted calculation methodology, the mechanical loss is considered to belong to a separate level of loss factors. It is therefore subtracted from the engine power before considering the relative magnitudes of the other loss components that have been analysed in this study.

Axial loss component

A3.15 The axial loss is set equal to the slip ratio $s_R = (nP_{0.7R} - V_A)/nP_{0.7R}$, while the relative magnitude of the axial loss component is expressed as $(1 - \eta_D)s_R$

where:

n = rate of revolution (per second) of the propeller

$P_{0.7R}$ = propeller pitch at 0.7 times the propeller radius R (m)

V_A = speed of advance of the propeller (m/s). Note: $V_A = (1 - w)V_S$.

The magnitude of the axial loss component is obtained as a fraction of the total loss $(1 - \eta_D)$.

Friction loss component

A3.16 This component of the loss requires calculation of the friction force acting against the rotation of the propeller blades. For this purpose, the following parameters have been calculated or determined on the basis of experience:

1. Total area of propeller blades, calculated based on the blade area ratio (m^2). This has been taken as the area where the friction is being generated;
2. Velocity in the plane of the propeller blades (m/s), calculated on the basis of the propeller's rotational velocity and its advance velocity. The rotational velocity is referred to 0.7 times the propeller's radius R;
3. A reduction of the velocity in the plane of the propeller because of the swirl of the fluid that has been introduced in the plane of the propeller, based on experience. The reduction generally amounts to approximately 4%; and
4. The friction coefficient has been determined from published results providing the magnitude of the friction coefficient as a function of a propeller's blade area ratio and the number of propeller blades. The values that are found are generally in the range $C_F = 0.008–0.010$.

The friction force at 0.7-times the propeller's radius R is then found as $F_{F0.7R} = 0.5C_{F\rho S}A_P V_F^2$. The resulting friction torque is given as $Q_{F0.7} = F_{F0.7R}0.7(D_P/2)$, while the resulting friction power is obtained from $P_F = 2\pi n Q_{F0.7R}$

where:

A_P = total area of propeller blades, calculated based on blade area ratio (m^2),

D_P = propeller diameter (m),

V_F = velocity in the plane of the propeller blades (m/s).

The relative value of the friction loss component is then found by dividing the resulting friction power P_F by the engine power, corrected for the loss due to the mechanical efficiency η_M.

Rotational loss component

A3.17 The rotational loss component is assumed to be the remaining relative loss obtained by subtracting the calculated relative axial loss and the relative friction loss from the total loss, expressed by $(1 - \eta_D)$.

A3.18 The accuracy of the resistance components discussed above is on the engineering level obtained by standard and accepted model test methods. This is also the case for the accuracy of the total propulsive loss $(1 - \eta_D)$.

A3.19 Regarding the components of the propulsive loss (axial, friction and rotation), simplified and practical calculation methods are adopted, and the accuracy to be expected must be seen in this light. It should be mentioned that the propulsive loss components that were calculated in this way agreed reasonably well with those obtained for one particular propeller, where similar components were obtained by a full CFD calculation.

STATISTICAL REGRESSION ANALYSIS MODEL

A3.20 In order to facilitate further analysis and achieve the estimation of energy consumption of a displacement ship in weather conditions, the present study adopts, as an intermediate step, the statistical regression analysis model for calm water conditions. Further, this means that the statistical regression method has been applied on the results that had been obtained from the previous step, which was based on MARINTEK's 2008 propulsion test database.

A3.21 Among various statistical regression-analysis-based methods for calculating the ship's total calm-water resistance (see, for an overview, Schneekluth and Bertram, 1998) is the "Hollenbach" (1998) method, which is one of the most popular and extensively used methods with general applicability. Since, the "Hollenbach" method provides a reliable prediction of the total calm-water resistance for modern displacement ships in the preliminary design stage, it has been chosen as a suitable tool in the present work. However, a detailed description of the "Hollenbach" method will not be given here, simply because the method is very extensive in its details, but an interested reader may found them in Hollenbach (1998).

APPROXIMATE ESTIMATION OF LOSS OF SPEED DUE TO ADDED RESISTANCE IN WEATHER CONDITIONS

A3.22 This section will provide the detailed description of a recently published approximate method for the prediction of loss of speed due to added resistance in weather conditions (irregular waves and wind) established by Kwon (2008). This approach is used by this work simply because the "Kwon" method is very new and therefore not yet very well known amongst the research community who are interested in the practical prediction of the involuntary drop in speed due to the effects of weather loading upon an advancing displacement type of ship.

A3.23 The percentage of speed loss as given by Kwon (2008) is expressed as:

$$\frac{\Delta V}{V_1} 100\% = C_\beta \, C_U \, C_{\text{Form}} \tag{1}$$

from which, by using the relationship $\Delta V = V_1 - V_2$, it follows that the ship speed in the selected weather conditions may be expressed as:

$$V_2 = V_1 - \left(\frac{\Delta V}{V_1} 100\%\right) \frac{1}{100\%} V_1 = V_1 - (C_\beta \, C_U \, C_{\text{Form}}) \frac{1}{100\%} V_1 \tag{2}$$

Here,

V_1	Design (nominal) operating ship speed in calm water conditions (no wind, no waves), given in m/s. Note: 1 knot = 0.514 444 4 . . . m/s, 1 m/s = 1.943 844 . . . knots;
V_2	Ship speed in the selected weather (wind and irregular waves) conditions, given in m/s. Note: $V_2 < V_1$. Note: 1 knot = 0.514 444 4 . . . m/s, 1 m/s = 1.943 844 . . . knots;
$\Delta V = V_1 - V_2$	Speed difference, given in m/s. Note: 1 knot = 0.514 444 4 . . . m/s, 1 m/s = 1.943 844 . . . knots;
C_β	Direction reduction coefficient, dependent on the weather direction angle (with respect to the ship's bow) and the Beaufort number *BN* (*Bft*). Note: C_β (see Table A3.1) is a non-dimensional number. Loading due to wind and sea is assumed to be from the same direction (angle) with respect to the ship's bow;
C_U	Speed reduction coefficient, dependent on the ship's block coefficient C_B, the loading conditions and the Froude number *Fn*. Note: C_U (see Table A3.2) is a non-dimensional number;

Table A3.1 *(Kwon, 2008)*

Weather direction	Direction angle (with respect to the ship's bow)	Direction reduction coefficient C_β
Head sea (irregular waves) and wind	0°	$2C_\beta = 2$
Bow sea (irregular waves) and wind	30° to 60°	$2C_\beta = 1.7 - 0.03(BN - 4)^2$
Beam sea (irregular waves) and wind	60° to 150°	$2C_\beta = 0.9 - 0.06(BN - 6)^2$
Following sea (irregular waves) and wind	150° to 180°	$2C_\beta = 0.4 - 0.03(BN - 8)^2$

Table A3.2 *(Kwon, 2008)*

Block coefficient C_B	Ship loading conditions	Speed reduction coefficient C_U
0.55	normal	$1.7 - 1.4Fn - 7.4(Fn)^2$
0.60	normal	$2.2 - 2.5Fn - 9.7(Fn)^2$
0.65	normal	$2.6 - 3.7Fn - 11.6(Fn)^2$
0.70	normal	$3.1 - 5.3Fn - 12.4(Fn)^2$
0.75	loaded or normal	$2.4 - 10.6Fn - 9.5(Fn)^2$
0.80	loaded or normal	$2.6 - 13.1Fn - 15.1(Fn)^2$
0.85	loaded or normal	$3.1 - 18.7Fn + 28.0(Fn)^2$
0.75	ballast	$2.6 - 12.5Fn - 13.5(Fn)^2$
0.80	ballast	$3.0 - 16.3Fn - 21.6(Fn)^2$
0.85	ballast	$3.4 - 20.9Fn + 31.8(Fn)^2$

C_{Form} Ship form coefficient, dependent on the ship type, the Beaufort number *BN* (*Bft*) and the ship displacement ∇, given in m^3. Note: C_{Form} (see Table A3.3) is a non-dimensional number. *BN* – Beaufort (non-dimensional) number (*Bft* – see Table A3.4).

Table A3.3 *(Kwon, 2008)*

Type of (displacement) ship	Ship form coefficient C_{Form}
All ships (except container ships) in loaded loading conditions	$0.5BN + BN^{6.5}/(2.7\nabla^{2/3})$
All ships (except container ships) in ballast loading conditions	$0.7BN + BN^{6.5}/(2.7\nabla^{2/3})$
Container ships in normal loading conditions	$0.5BN + BN^{6.5}/(22.0\nabla^{2/3})$

$Fn = V/\sqrt{L_{pp}g}$ Froude number associated with the design (nominal) operating ship speed V_1 (m/s) in calm water conditions, L_{pp} is the ship length between perpendiculars, given in metres, $g = 9.806\ 65$ m/s^2 is the acceleration of gravity;

C_B Ship's block coefficient.

A3.24 In order to apply the "Kwon" method, the following four tables need to be used. The first three tables, namely Tables A3.1, A3.2 and A3.3, give expressions for the direction reduction coefficient C_β, the speed reduction coefficient C_U and the ship's form coefficient C_{Form}, respectively, while Table A3.4 provides values for the Beaufort number (*BN* – *Bft*) which describe the sea state and the wind strength for the North Sea (Henschke, 1965).

A3.25 As can be seen from the above set of tables, the speed loss can be estimated for a general type of ship advancing with arbitrary forward speed on a straight-line course and experiencing irregular wave and wind field from various directions. In addition, the expressions that are given within the above set of tables give insights into the ship loading conditions (expressed as "normal", "loaded" or "ballast" loading conditions) under which the ship in question currently operates. Consequently, this has an important role

Table A3.4 *Wind strengths in Beaufort BN (Bft) and sea strengths for the North Sea, coupled with wind strengths (Henschke, 1965)*

Bft	Wind description	Wind speed [m/s]
0	No wind	0.0–0.2
1	Gentle current of air	03–1.5
2	Gentle breeze	1.6–3.3
3	Light breeze	3.4–5.4
4	Moderate breeze	5.5–7.9
5	Fresh breeze	8.0–10.7
6	Strong wind	10.8–13.8
7	Stiff wind	13.9–17.1
8	Violent wind	17.2–20.7
9	Storm	20.8–24.4
10	Violent storm	24.5–28.3
11	Hurricane-like storm	28.5–32.7
12	Hurricane	> 32.7

			Approximate average	
Sea scale	Bft	Sea description	Wave height [m]	Wavelength [m]
0	0	Smooth sea	–	–
1	1	Calm, rippling sea	0–0.5	0–10
2	2–3	Gentle sea	0.5–0.75	10–12.5
3	4	Light sea	0.75–1.25	12.5–22.5
4	5	Moderate sea	1.25–2.0	22.5–37.5
5	6	Rough sea	2.0–3.5	37.5–60.0
6	7	Very rough sea	3.5–6.0	60.0–105.0
7	8–9	High sea	>6.0	>105.0
8	10	Very high sea	up to 20	up to 600
9	11–12	Extremely heavy sen	up to 20	up to 600

in the prediction of fuel consumption and of emissions of CO_2, GHGs and solid particles which are of interest for any modern shipping company today.

A3.26 At the end of this section, it should be emphasized that the application of the "Kwon" (2008) method is dependent on knowledge of only a few parameters, amongst which are: weather conditions, ship's block coefficient, type of (displacement) ship, ship's displacement, approach (initial) forward speed (expressed through the Froude number) and the Beaufort number. Having these parameters available, the percentage of speed loss or the ship's speed in selected weather conditions can be readily estimated by using the expressions (1) or (2), respectively.

VERIFICATION OF THE APPROXIMATE FORMULAE

A3.27 The approximate formulae for estimation of speed loss according to the "Kwon" (2008) method have been verified on two significantly different types of ships, characterized by block coefficients C_B of 0.84 and 0.62. Figure A3.2 shows the predicted percentage of speed drop for a tanker and container type of ship advancing on a straight linear course on considerably different Froude numbers *Fn* of 0.15 and 0.25, respectively, while experiencing head weather (irregular sea and wind) conditions having various strengths described by Beaufort numbers *BN* in the range from 1 to 8.

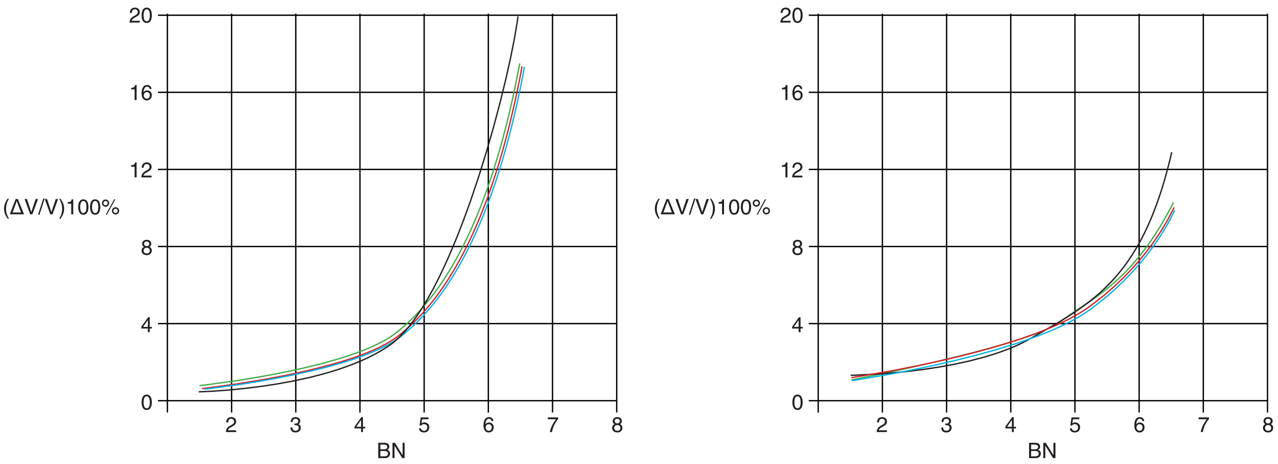


Figure A3.2 Speed loss (drop) of a ship in irregular head waves and wind (waves and wind from the same direction 180°) – comparison between the approximate formulae and detailed calculations for (a) Large tanker (loaded and/or normal condition), displacement volume $\nabla = 350{,}000\ m^3$, $Fn = 0.15$, $C_B = 0.84$, $L_{pp} = 336.0$ m; (b) Large container ship (loaded and/or normal condition), displacement volume $\nabla = 60{,}200\ m^3$, $Fn = 0.25$, $C_B = 0.62$

Note:

Approximate formula (Townsin and Kwon, 1982)
Approximate formula: Tanker C_B = 0.80, Container C_B = 0.60 (Kwon, 2008)
Approximate formula: Tanker C_B = 0.85, Container C_B = 0.65 (Kwon, 2008)
Detailed calculation (Kwon, 1982)

A3.28 The results for percentage of speed drop that were obtained by using the "Kwon" (2008) approximate method are compared with detailed hydrodynamic calculations provided by Kwon (1982). As can be seen from Figure A3.2, a very good agreement between the different mentioned methods is present which, on the other hand, justifies the application of the "Kwon" (2008) method. Furthermore, this means that reliable prediction of speed loss can be achieved in an easier and quick way by avoiding complex hydrodynamic calculations (Kwon, 1982), which is of practical importance for the present study orientated on the prediction of energy consumption and emissions of CO_2, GHGs and solid particles.

PERFORMANCE IN HEAD WEATHER (IRREGULAR WAVES AND WIND) CONDITIONS

A3.29 Performances of the displacement ships (classified according to the group classification introduced previously) are discussed now from the perspective of delivered power in (head) weather conditions (see Tigure A3.3). As has already been mentioned, the "Hollenbach" (1998) method is applied to predict the curve of delivered power in calm water. The same curve is further used in combination with the "Kwon" (2008) method, which predicts involuntary speed loss in respect to selected ship type and weather conditions according to Tables A3.1 to A3.4. As can be seen from Tigure A3.3, an application of the "Kwon" (2008) method provides prediction of the curve of delivered power for head weather conditions versus ship speed, given in knots. At the same time, the involuntary drop in speed is readily available under the assumption that the selected ship is able to provide constant output of delivered power from its main propulsive plant in the chosen head weather conditions.

A3.30 On the other hand, it should be noticed that the requirement for maintaining constant ship speed in calm water and weather conditions invokes a very steep gradient of the curve for delivered power in head weather conditions in respect to calm water. Consequently, this very steep gradient will cause significant fuel consumption and therefore emission of CO_2, GHGs and solid particles into the environment surrounding an advancing ship. Furthermore, in certain situations, the peak point of delivered power in head weather conditions may not be available, due to the fact that it is dependent on several parameters, amongst which are the condition of the ship and the condition of the main power plant, economically justified requirements associated with the ship's route, etc.

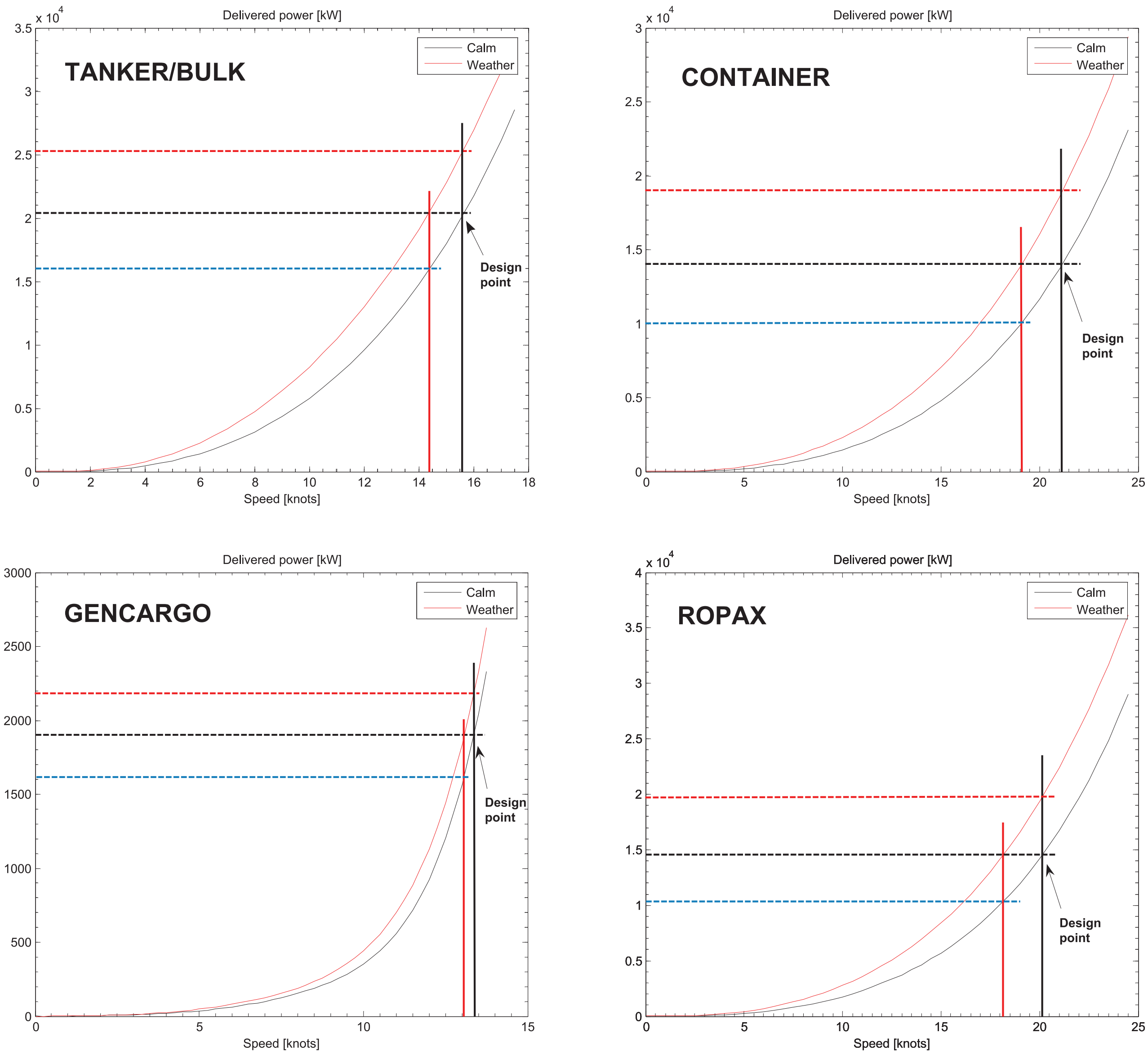


Figure A3.3 Speed loss (drop) at constant delivered power P_D or at increased delivered power P_D, at constant speed, of the advance of vessels in head weather conditions (irregular waves and wind from the same direction 180°) for four different types of ships, according to MARINTEK's 2008 direct model tests database, with the assumption of Beaufort number *BN* (*Bft*) = 6 for Tanker/Bulk, *BN* (*Bft*) = 6 for Container, *BN* (*Bft*) = 3 for GenCargo, *BN* (*Bft*) = 6 for RoPax

Note:
—— Delivered power P_D in calm water (Hollenbach, 1998)
—— Delivered power P_D in head weather conditions (Kwon, 2008)

REFERENCES

1 AEA (2008). AEA (September 2008) Greenhouse gas emissions from shipping: trends, projections and abatement potential.
2 Bertram, V. (2000). *Practical Ship Hydrodynamics*. Butterworth–Heinemann. Oxford, UK.
3 Carlton, J.S. (1994). *Marine Propellers and Propulsion*. Butterworth–Heineman, Oxford, UK.
4 Faltinsen, O.M. (1990). *Sea Loads on Ships and Offshore Structures*. Cambridge University Press, UK.
5 Faltinsen, O.M. (2005). *Hydrodynamics of High-Speed Marine Vehicles*. Cambridge University Press, UK.
6 Faltinsen, O.M., Minsaas, K., Liapis, N. and Skjørdal, S.O. (1980). "Prediction of resistance and propulsion of a ship in a seaway". In Proceedings of the 13th Symposium on Naval Hydrodynamics, pp. 505–529, Tokyo, Japan.
7 Guang, S.H. (1987). "Mathematical modeling of ship speed-loss due to wind and seas". *Oceans*, 19: 494–499.
8 Henschke, W. (1965). *Schiffbautechnisches Handbuch*. 2nd edn, Verlag Technik, Berlin.

9 Hollenbach, K.U. (1998). "Estimating resistance and propulsion for single-screw and twin-screw ships". *Ship Technology Research*, 45: 72–76.

10 Holtrop, J. and Mennen, G.G.J. (1982). "An approximate power prediction method". *Int. Shipbuild. Progr.*, 29: 166–170.

11 Kwon, Y.J. (1982). "The effects of weather, particularly short sea waves, on ship speed performance". PhD thesis. University of Newcastle upon Tyne, UK.

12 Kwon, Y.J. (2008). "Speed loss due to added resistance in wind and waves". *The Naval Architect*, 3: 14–16.

13 Larsson, L. and Baba, E. (1996). "Ship resistance and flow computations". *Advances in Marine Hydrodynamics*, M. Ohkusu (ed.), Comp. Mech. Publications.

14 Lewis, E.V. (ed.) (1989). *Principles of Naval Architecture*, Vol. I, II and III. SNAME, Jersey City, New Jersey, USA.

15 MARINTEK (2008). "Propulsive tests database". Internal documentation, Trondheim, Norway.

16 Martinussen, K. (2008). Memo: Calculation of calm water ship resistance and propulsive forces. Internal MARINTEK document, Trondheim, Norway.

17 Privette, R.M. (1999). "PEM fuel cell evaluation for navy surface ship applications". 34th Intersociety Energy Conversion Engineering Conference, Vancouver, Canada.

18 Rawson, K.J. and Tupper, E.C. (2001). *Basic Ship Theory*, Vol. 1 and Vol. 2. Butterworth-Heinemann, Oxford, UK.

19 Schneekluth, H. and Bertram, V. (1998). *Ship design for efficiency and economy*. Butterworth-Heinemann, Oxford, UK.

20 Seif, M.S. and Tavakoli, M.T. (2004) New Technologies for Reducing Fuel Consumption in Marine Vehicles. The 16th Symposium on Theory and Practice of Shipbuilding (XVI SORTA Symposium), Plitvice, Croatia.

21 Skejic, R. and Faltinsen, O.M. (2008). "A unified seakeeping and maneuvering analysis of ships in regular waves". *J. of Marine Science and Technology*, 13: 371–394, doi:10.1007/s00773-008-0025-2, http://www.springerlink.com/content/88373xm3g12h4067/fulltext.pdf

22 Townsin, R.L. and Kwon, Y.J. (1983). "Approximate formulae for the speed loss due to added resistance in wind and waves". *Transactions RINA*, 125: 199–207.

23 Townsin, R.L., Kwon, Y.J., Baree, M.S. and Kim, D.Y. (1993). "Estimating the influence of weather on ship performance". *Transactions RINA*, 135: 191–209.

24 Townsin, R.L. (2003). "The Ship Hull Fouling Penalty", *Biofouling*, 19(1): 9–15.

Appendix 4

Estimation of CO_2 marginal abatement costs for shipping

INTRODUCTION

A4.1 The different measures that contribute to the abatement of emissions of CO_2 in maritime transport can be illustrated in a marginal abatement cost curve (MACC). A MACC depicts the maximum abatement potential of abatement measures that do not exclude each other, sorted by their cost efficiency. We derived such a MACC for 2020 (see Chapter 5 and below). Twenty-five different measures, allocated to the following groups, were thereby taken into account:

1. Propeller maintenance;
2. Propeller/propulsion system upgrades;
3. Hull coating and maintenance;
4. Voyage and operations options;
5. Main engine retrofit measures;
6. Retrofit hull improvements;
7. Auxiliary systems;
8. Other retrofit options;
9. Speed reduction; and
10. Air lubrication.

The groups were chosen such that measures from different groups do not exclude each other. Measures from the same group exclude each other or are, most probably, not used together. Most of the measures that are accounted for are retrofit measures. In paragraph A4.22 you find a list of the individual measures.

A4.2 The MACC gives the cost efficiency and the maximum abatement potential for the different groups. Although the cost efficiency and the maximum abatement potential have been calculated for the individual measures, an estimation per group is being used. This is due to the fact that uncertainty, particularly about the costs of the abatement measures, is still very high. For the same reason, we distinguished between three estimates for every measure group: a low bound, a high bound, as well as a central estimate.

A4.3 In the following we will first present the MACC for a price of US$500/tonne for bunker fuel and an interest rate of 4%. Subsequently, we will briefly go into the changes of the MACC that are implied by a change of the price of bunker fuel or by a change of the interest rate. The derivation of the cost efficiency and the maximum abatement potential for the individual measures is then described in greater detail.

THE MARGINAL CO_2 ABATEMENT COST CURVE FOR 2020

A4.4 In Figure A4.1 the marginal CO_2 abatement cost curve for 2020 is given for a fuel price of US$500/tonne and an interest rate of 4%.

A4.5 The maximum abatement potential of the measures that are taken into account lies within a range of 210 to 440 Mt of CO_2, which is about 15–30% of the projected total emissions of the vessel types taken

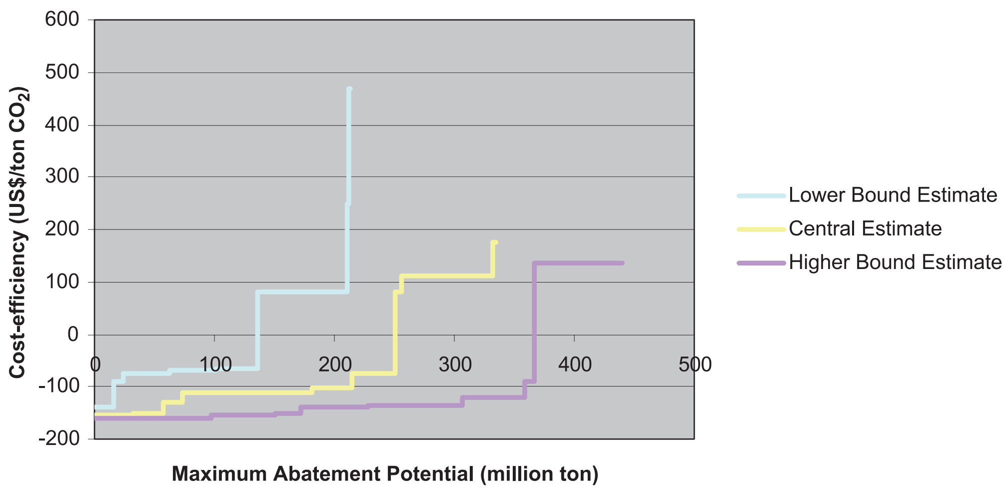


Figure A4.1 *Marginal CO_2 abatement cost curve for 2020, a fuel price of US$500/tonne and an interest rate of 4%*

into account.[1] There is a range of measures whose cost efficiency is negative. That means that these measures are profitable even when CO_2 emissions have no price. The range of the maximum abatement potential of these measures is 135 to 365 Mt of CO_2 and lies, for the central estimate, at about 255 Mt. In Table A4.1, the cost efficiency and the maximum abatement potential are given for the different groups of measures.

Table A4.1 *Approximate cost efficiency and maximum abatement potential for the different groups of measures* (2020, fuel price is US$500/tonne, interest rate is 4%)*

	Cost efficiency (US$/tonne of CO_2)	Maximum abatement potential (Mt)
	Central estimate (low bound estimate / high bound estimate)	
Retrofit hull measures	–155 (–140/–160)	30 (10/55)
Voyage and operational options	–150 (–140/–160)	25 (5/45)
Air lubrication	–130 (–90/–150)	20 (10/25)
Propeller/propulsion upgrades	–115 (–70/–155)	50 (45/60)
Other retrofit options	–110 (–75/–135)	70 (40/100)
Hull coating and maintenance	–105 (–65/–140)	40 (15/65)
Propeller maintenance	–75 (–65/–120)	45 (25/65)
Auxiliary systems	80 (250/–90)	5 (2/10)
Speed reduction	110 (80/135)	100 (90/110)
Main engine improvements	175 (470/–120)	5 (1/10)

* Note that, since the measures are sorted by their cost efficiency, the order of the measures differs for the different estimates.

A4.6 Speed reduction, other retrofit options and propeller/propulsion upgrades show the highest abatement potential, whereas retrofit hull measures, voyage and operational options, and air lubrication feature the best cost efficiencies.

A4.7 The MACC above has been derived for a bunker fuel price of US$500/tonne. Figure A4.2 illustrates, for the central estimate, the impact of a change in fuel price on the MACC. The maximum abatement potential does not change with the price of bunker fuel, whereas the cost efficiency of the measures improves. This means that every level of CO_2 abatement can be reached at lower costs, and also that the maximum abatement potential of those measures with a non-positive cost efficiency does increase. Note that, for a fuel price of US$1,500/tonne, the cost efficiency of all of the measures that were taken into account is negative.

1 As a baseline, we employ the A1B scenario of the IMO 2020 prediction (IMO, 2008), with the demand level being medium and both the speed reduction and the transport efficiency level being low. The total baseline emissions for the vessel types that were taken into account in this study (see below) amount accordingly to about 1250 Mt.

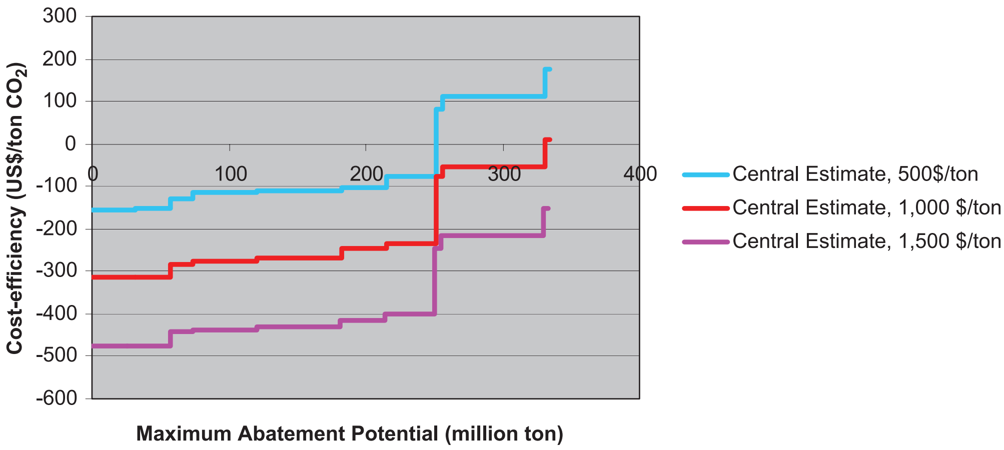


Figure A4.2 *Marginal CO_2 abatement cost curve for alternative fuel prices, 2020, central estimate only*

A4.8 The MACC as shown in Figure A4.1 has been derived for an interest rate of 4%. Figure A4.3 illustrates how the MACC would change if a higher interest rate, in this case 16%, was applied. A higher interest rate leads to a rise of the measures' annuities[2] and thus to an aggravation of the cost efficiency. The MACC therefore moves upwards.

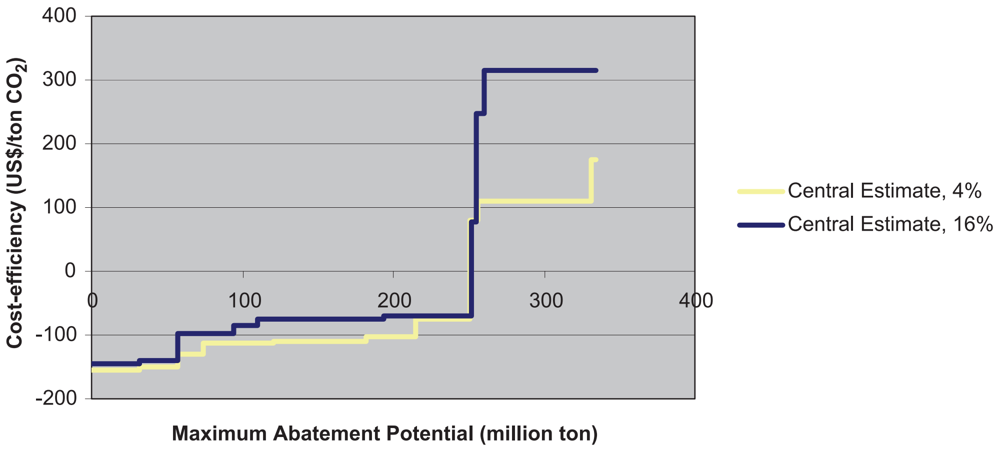


Figure A4.3 *Marginal CO_2 abatement cost curves, 2020, for a fuel price of US$500/tonne and alternative interest rates, central estimate only*

COST EFFICIENCY AND MAXIMUM ABATEMENT POTENTIAL

Methodology and general assumptions

A4.9 The cost efficiency of an abatement measure is defined as its net costs for reducing a unit of CO_2 emissions in a certain year. The net costs are the costs due to the application of the measure minus the savings of fuel expenditure that are achieved by implementing it. Note that, when there is no regulation of CO_2 at all, a measure is, according to this definition, only profitable when its cost efficiency is negative.

A4.10 For the calculation of the cost efficiency, we allow for a low and a high reduction potential of a measure. As will be outlined below, the uncertainty about the costs of the measures is relatively high. That is why we also work with a high and a low cost estimate, leading, together with the two reduction scenarios,

2 As will be outlined below, the non-recurring costs of an abatement measure are considered as annuities when calculating the cost efficiency of a measure.

to four different cost efficiency numbers per measure.[3] The low and the high cost estimate are thereby the same for the two reduction scenarios.

A4.11 As to the costs of an abatement measure, we differentiate between non-recurring costs and annual recurring costs. The non-recurring costs are translated into annual costs by calculating an annuity. The number of years over which the investment is thereby spread depends on the expected lifetime of a measure. In Table A4.2, an overview is given of the expected lifetime and the related assumption that is being made with respect to the years over which the investment is spread.

Table A4.2 *Number of years over which non-recurring costs are spread, depending on the expected lifetime of a measure*

Expected lifetime of measure	Investment/non-recurring costs are spread over . . . years
≤ 10 years	actual expected lifetime
11–30 years	10 years
≥ 30 years	30 years

A4.12 For a measure with an expected lifetime of 10 years or less, the spread is carried out over the actual expected lifetime. For those measures whose expected lifetime is between 10 and 30 years, the investment is spread over 10 years, thus implicitly assuming a reinvestment after 10 years.[4] For those measures whose expected lifetime is 30 years or more, the investment is spread over 30 years.

A4.13 The interest rate that enters the calculation of the annuity is allowed to vary in the model.

A4.14 The data for bunker fuel consumption are taken from the IMO fleet prediction for 2020.[5] Just as for the interest rate, the price of bunker fuel is allowed to vary in the model. We do not differentiate between prices for different qualities of fuel.

A4.15 The maximum abatement potential of a measure is the maximum level of abatement that can be achieved by a measure in a certain year, i.e. the abatement level when all the vessels to which a measure can be applied actually make use of it. In order to calculate the maximum abatement potential of a measure, we thus need to know the ship types that are able to make use of a measure and also the number of vessels that can apply a measure in a certain year. For the latter, it is crucial to differentiate between retrofit and non-retrofit measures. Non-retrofit measures can only be applied to newly built ships. We therefore have to determine the number of new ships that enter the market between the year of introduction of the measure onto the market and the year under consideration. From the IMO fleet inventory we know the total number of ships that are in place per ship class in 2007. The IMO prediction provides us with this information for 2020. However, we neither dispose of information on the age structure of the fleet in the two years, nor do we have information on the fleet in the period 2008–2020. In order to fill this gap, we make the following four assumptions:

1. In 2007, no new ships enter the market;
2. The total number of ships per ship class rises/decreases linearly in the period between 2007 and 2020;
3. A vessel always reaches an age of 30 years/is no longer used when turning 31; and

3 In paragraphs A4.18 to A4.69, the cost efficiency and the abatement potential of the individual measures are presented for the four cases: low reduction potential and low cost estimate, low reduction potential and high cost estimate, high reduction potential and low cost estimate, and high reduction potential and high cost estimate. These numbers were the basis for the estimation of the cost efficiency and the abatement potential for the 10 measure groups that are given in the MACC. Here, however, only three different estimations are given per group: low bound, high bound and central estimation.

4 The reinvestment only takes place if the lifetime of the vessel allows for a spread of the investment over the following 10 years (see also the section on the maximum abatement potential).

5 More specifically, we employ the A1B scenario of the IMO 2020 prediction, with the demand level being medium and both the speed reduction and the transport efficiency level being low.

4. In 2007, ships are uniformly distributed as to the age, i.e. 1/30 of the ships in 2007 are one year old, 1/30 of the ships in 2007 are two years old, etc.[6]

Given these assumptions, the number of new ships that enter the market in a year is equal to the difference between the total number of ships in that very year and the total number of ships in the previous year minus one thirtieth of the total number of ships in 2007.

A4.16 Deriving size and age structure of the fleet for the different years also allows us to determine the number of ships that can adopt a retrofit measure. Since it is implausible that a retrofit measure is applied to a very old vessel, we additionally assume that, depending on the expected lifetime of a measure, certain vintages of vessel are not retrofitted with emissions-saving equipment. More specifically, a retrofit measure is assumed to be applied only to those ships whose remaining lifetime allows the investment to be fully spread over the years that are underlying the annuity calculation (see above). As an example: When a measure has an expected lifetime of five years, its non-recurring costs are spread over five years. In the year of introduction of a measure onto the market, the last four vintages of a ship class will then not apply that retrofit measure.

A4.17 Note that possible shortages on the supply side of the measure or irrational behaviour on the demand side for the measure are not taken into account when the maximum abatement potential is being calculated.

Results and measure-specific assumptions

A4.18 In the following we will present the cost efficiency and the maximum abatement potential of the individual CO_2 abatement measures that have been taken into account for the MACC. Per measure, we will give information on the applicability of the measure, the application so far, and on the costs and reduction potentials that are underlying the results. The results will be given on a sector level, i.e. aggregated over all ship types. It should be borne in mind that measures that turn out to be unprofitable on the sector level may nevertheless be profitable for a certain ship type.

A4.19 The results presented below are given for a social interest rate. The average return on 10-year State bonds in the United States and Europe fluctuated during the past five years between 3% and 5%. That is why we decided to work with an interest rate of 4%. The bunker fuel price is assumed to be US$500/tonne.

A4.20 The ship types we have taken into account are as listed in Table A1.8 of Appendix 1 (Estimate of 2007 fuel consumption by international shipping). However, fishing vessels, vessels for offshore purposes, service vessels (for example, research vessels) and yachts were not accounted for.

A4.21 According to the IMO study (2008) [5], the total CO_2 emissions of the vessels taken into account will be about 1,250 Mt in 2020.

A4.22 In order to set up the marginal abatement cost curve, we grouped the 25 different measures as shown above. The groups were chosen such that measures from different groups do not exclude each other and that measures from the same group exclude each other or are most likely not used together. As indicated in the list below, only two of the measures analysed can be applied to new ships only. All of the other measures can be retrofitted.

1. **Propeller maintenance**
   - Propeller performance monitoring
   - Propeller brushing (increased frequency)
   - Propeller brushing
2. **Propeller/propulsion system upgrades**
   - Propeller/rudder upgrade
   - Propeller upgrade (winglet, nozzle)
   - Propeller boss cap fins

6 The only ship type where the number of ships does decline more than (13/30) in the period between 2007 and 2020 are chemical tankers with a deadweight ton up to 4,999. Here we assume that no new ships enter the market between 2007 and 2020.

3. **Hull coating and maintenance**
   - Hull performance monitoring
   - Hull coating (two types)
   - Hull brushing
   - Hull hydroblasting (underwater)
   - Dry-dock full blast (as opposed to spot blast)
4. **Voyage and operations options**
   - Shaft power meter (performance monitoring)
   - Fuel consumption meter (performance monitoring)
   - Weather routeing
   - Autopilot upgrade/adjustment
5. **Main engine retrofit**
   - Main engine tuning
   - Common rail upgrade
6. **Retrofit hull improvements**
   - Transverse thruster opening (flow optimization, grids)
7. **Auxiliary systems**
   - Low-energy/low-heat lighting
   - Speed control pumps and fans
   - Power management (new ships only)
8. **Other retrofit options**: towing kite
9. **Speed reduction**
10. **Air lubrication** (new ships only)

For every measure, we will present in the following the crucial assumptions and the resulting cost efficiency as well as the maximum abatement potential. The measures are presented in the following order: we will first present the last three groups (i.e. Other retrofit options: towing kite, Speed reduction and Air lubrication) and the hull coatings in more detail and will then present the other measures briefly in the order of the grouping above.

A4.23 Here, beforehand, is an overview of the assumptions that have been made as to which ship type the individual measures can be applied.

OTHER RETROFIT OPTIONS: TOWING KITE

A4.24 A towing kite makes use of wind energy to substitute power of the engine. The system can be retrofitted. It can be used on vessels with a minimum length of 30 m and works best on ships with an average speed no higher than 16 knots. Due to this speed restriction, only tankers (crude oil, product, chemical, LPG, LNG, other) and bulk carriers are being considered as potential users (see Corbett *et al.* (2006) [6] for the average speed per vessel type).

A4.25 Until now (December 2008), kites that have an area of up to 640 m^2 for cargo vessels, fishing trawlers and yachts are available and kite systems have been installed on three vessels: a testing ship and two commercial ships, both multipurpose cargo vessels. One of the commercial ships is a newly built vessel, the other was retrofitted. Both vessels are equipped with a 160 m^2 kite. Kites up to an area of 5,000 m^2 are planned. For the calculation of the cost efficiency and the maximum abatement potential

Table A4.3 *Applicability of the individual abatement measures to the different ship types as assumed in the analysis*

	Applicability of measures as assumed in the study
Propeller maintenance	
Propeller performance monitoring	All ship types.
Propeller brushing (increased frequency)	All ship types.
Propeller brushing	All ship types.
Propeller/propulsion system upgrades	
Propeller/rudder upgrade	All ship types other than ferries and cruise ships.
Propeller upgrade (winglet, nozzle)	Tankers (crude oil, product, chemical, LPG, LNG, and other) only.
Propeller boss cap fins	All ship types.
Hull coating and maintenance	
Hull performance monitoring	All ship types.
Hull coating (two types)	All ship types.
Hull brushing	All ship types.
Hull hydroblasting (underwater)	All ship types.
Dry-dock full blast (as opposed to spot blast)	All ship types; assumed to be applied to old ships only.
Voyage and operations options	
Shaft power meter (performance monitoring)	All ship types.
Fuel consumption meter (performance monitoring)	All ship types.
Weather routeing	
Autopilot upgrade/adjustment	All ship types.
Main engine retrofit	All ship types other than ferries and cruise ships.
Main engine tuning	All ship types other than ferries and cruise ships.
Common rail upgrade	All ship types.
Retrofit hull improvements	
Transverse thruster opening (flow optimization, grids)	All ship types.
Auxiliary systems	
Low-energy/low-heat lighting	Ferries and cruise ships only.
Speed control pumps and fans	All ship types.
Power management	Newly built ships only; all ship types.
Other retrofit options	
Towing kite	Bulk carriers, tankers (crude oil, product, chemical, LPG, LNG, and other)
Speed reduction	
10% speed reduction of the entire fleet	All ship types.
Air lubrication	
Air lubrication	Newly built ships only; crude oil tankers and bulk carriers > 60,000 dwt, LPG tankers > 50,000 m^3, all LNG tankers, full container vessels > 2,000 TEU

of a towing kite, we assume that, in 2020, kites up to 5,000 m^2 are available in the market. In Table A4.4, our allocation of the different kite sizes to the ship types is given.

A4.26 It is difficult to determine the the potential reduction of fuel useage (and hence of CO_2 emitted) of a towing kite, since the potential does not only depend on the area of a kite applied, but also on the route a vessel takes and the respective weather conditions. In Table A4.5, the engine equivalent powers we used for the different kite sizes are given. These numbers hold under standard conditions.[7]

7 The standard conditions are defined as follows: the vessel cruises at a speed of 10 knots at a true wind course of 130°**, the wind speed is 25 knots, waves are up to 60 cm high and the kite is manoeuvred dynamically.**

Table A4.4 *Surface areas of kites assumed to be applied in 2020 to the different ship types*

Ship type		Kites applied in 2020 (m^2)
Crude oil tanker	200,000+ dwt	5,000
Crude oil tanker	120,000–199,999 dwt	2,500
Crude oil tanker	80,000–119,999 dwt	1,280
Crude oil tanker	60,000–79,999 dwt	1,280
Crude oil tanker	10,000–59,999 dwt	640
Crude oil tanker	0–9,999 dwt	160
Product tanker	60,000+ dwt	1,280
Product tanker	20,000–59,999 dwt	640
Product tanker	10,000–19,999 dwt	320
Product tanker	5,000–9,999 dwt	320
Product tanker	0–4,999 dwt	160
Chemical tanker	20,000+ dwt	1,280
Chemical tanker	10,000–19,999 dwt	320
Chemical tanker	5,000–9,999 dwt	320
Chemical tanker	0–4,999 dwt	160
LPG tanker	50,000+ m^3	640
LPG tanker	0–49,999 m^3	320
LNG tanker	200,000+ m^3	1,280
LNG tanker	0–199,999 m^3	640
Other tanker	Other (small)	160
Bulk carrier	200,000+ dwt	2,500
Bulk carrier	100,000–199,999 dwt	2,500
Bulk carrier	60,000–99,999 dwt	1,280
Bulk carrier	35,000–59,999 dwt	640
Bulk carrier	10,000–34,999 dwt	640
Bulk carrier	0–9,999 dwt	160

Table A4.5 *Approximate engine equivalent power used for the different kites*

Kite area (m^2)	Engine equivalent power under standard conditions (kW)
160	600
320	1,200
640	2,500
1,280	4,900
2,500	9,600
5,000	19,200

A4.27 The cost data that were used in our calculations are given in Table A4.6. The purchase price varies with the kite system that is used. Installation and operational costs are taken to be a certain share of the purchase price. For simplicity, we use the same percentage for installation costs of retrofit and non-retrofit systems.

A4.28 Note that the cost data are such that possible reinvestments during the lifetime of a vessel, i.e. 30 years, are included. The resulting approximate cost efficiency and maximum abatement potential are given in Table A4.7. The low (high) reduction potential scenario thereby corresponds to the case that the kite can be used 1/3 (2/3) of the days at sea.

Table A4.6 *Approximate estimates of cost entries for a towing kite as used in the analysis*

			Kite area (m^2)				
			320	**640**	**1,280**	**2,500**	**5,000**
Purchase price (US$ thousand)			480	920	1,755	2,590	3,430
Installation costs	Assumed % of purchase price		7.5%	7.5%	7.5%	7.5%	7.5%
	Resulting installation costs (US$ thousand)		26	50	96	142	188
Operational costs per annum	Assumed % of purchase price		5–7%	7–9%	9–11%	11–13%	13–15%
	Resulting operational costs per annum (US$ thousand)	Low	25	65	160	285	445
		High	35	85	195	335	515

Table A4.7 *Approximate cost efficiency and maximum abatement potential of towing kites (price of bunker fuel US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	**High cost estimate**	**in Mt**	**% of total emissions**
2020	Low reduction potential	–85	–75	37.1	3.0%
	High reduction potential	–135	–130	100.9	8.0%

SPEED REDUCTION

A4.29 Emissions from a vessel are roughly related to the square of the vessel's speed. A speed reduction of, for example, 10% can thus lead to a reduction of emissions of 19% on a tonne-kilometre basis. Since a reduction of speed affects the amount of freight that can be transported by a vessel over a particular time period, an operator has to make use of additional capacity in order to avoid losses (AEA, 2008 [1]). In our analysis we assume that the extra capacity is provided by new vessels. In other words, the basic assumption is that, in the initial situation, the market is in an equilibrium, with no overcapacity, and that reduction of ship's speed will not result in higher load factors. Another crucial assumption in the analysis is that all of the vessels in the market reduce their speed by the same percentage and also that the number of new vessels that consequently have to be purchased is determined as if the global fleet was in the possession of a single owner. The fraction of ships that need to be purchased is determined as given in this formula: $\frac{1}{(1 - \text{speed reduction in } \%)} - 1$; halving the speed would require doubling the fleet.

A4.30 The non-recurring costs of the measure "speed reduction" are the costs for purchasing the extra vessels. The recurring costs are the annual operational costs of the extra vessels, including the fuel consumption at the lower speed. The emission reduction of the "original" fleet has to be offset against the extra emissions of the additional vessels.

A4.31 The prices for the newly built vessels are deduced from UNCTAD (2008) [6]. Since the prices for newly built vessels tend to be very volatile, with 2007 being a year with above average prices when looking at the past 10 years, we applied a correction factor of 0.7 to the data for 2007.

A4.32 We assessed the operational costs, excluding the fuel costs, for every ship type to be between US$6,000 and US$8,000 per day. Four ship types were not taken into account. Cruise vessels and ferries were excluded, because they have to stick to a route/time scheme. Ro-Ro and vehicle carriers were also not accounted for, since UNCTAD (2008) [6] gives no indication for the prices of newly built vessels of these types. In Table A4.8 the results for a speed reduction of 10% are given.

A4.33 It has to be pointed out that the figures have to be considered as a conservative estimation, since a speed reduction in this analysis is always assumed to be corrected for by the purchase of new ships. Usage of possible overcapacity would make the measure certainly more cost-effective.

A4.34 It also has to be emphasized that the estimates that are presented in Table A4.8 are fleet average figures. They show the abatement potential and the cost efficiency of a fleet-wide speed reduction of 10%.

Table A4.8 *Approximate cost efficiency and maximum abatement potential for a speed reduction by 10% of all vessels (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	10% speed reduction of the entire fleet	80	135	98.7	7.9%

While, for some ship types, such a speed reduction would be cost-effective, for others it is not. In general, faster ships and larger ships demonstrate a better cost efficiency than smaller and slower ships.

AIR LUBRICATION

A4.35 The frictional resistance of a vessel's hull can be reduced by a so-called "air-cavity system" (ACS). The ACS is a non-retrofit measure whose lifetime is assumed to be 30 years. Tankers, bulk carriers and container vessels may make use of the system. Since the length of a vessel should be minimal 225 metres (LOA), we decided to consider the following vessels as potential users:

- Crude oil tanker and bulk carriers >60,000 dwt;
- LPG tankers with 50,000 m^3 capacity and more;
- All LNG tankers; and
- Full container vessels >2,000 TEU.

Recently, the first sea-trial with a test ship and operational tests in open water have been conducted. The technology was commercially available at the end of 2008.

A4.36 As to the potential reduction in fuel consumption and CO_2 emissions, the producer gives the following ranges: 10–15% for tanker and bulkers and 5–9% for container vessels. We used in our analysis half of this lower bound as the low reduction potential and the high reduction potential as given by the producer.

A4.37 Operational costs of an ACS translate into 0.3 to 0.5 tonnes of fuel per day, depending on sea conditions. Note that researchers from the Stichting FOM and the University of Twente pointed out that the potential fuel savings of a system like the air-cavity system depend highly on the smoothness of the hull. Good maintenance is thus required to actually realize the projected fuel savings. The operational costs for maintenance may therefore rise due to the application of an ACS. These extra costs are here not taken into account.

A4.38 The incremental non-recurring costs are expected to be 2–3% of the price of a conventional newly built vessel (without ACS).

A4.39 Again, we deduced the prices for newbuilts from UNCTAD (2008) [6], applying a correction factor of 0.7. In Table A4.9 you find an overview of the prices that were used in this analysis.

A4.40 Taking the information together, the resulting cost efficiency and the maximum abatement potential of an air-cavity system are as given in Table A4.10.

Antifouling hull coatings

A4.41 By reducing the frictional resistance of a hull, consumption of bunker fuel and thus emissions of CO_2 can be reduced. One way of reducing the frictional resistance is to enhance the smoothness of a hull by means of coatings that prevent/reduce fouling.

A4.42 We tried to estimate the cost efficiency and the maximum abatement potential of two different coatings, which we will call, in the following, "coating 1" and "coating 2". We therefore had to make an estimation of the extra costs that have to be incurred and the extra benefits that can be reaped by using these coatings in comparison to regular TBT-free coatings. In the following we will briefly describe the

Table A4.9 *Prices for newly built vessels, deduced from UNCTAD (2008) [6]*

		Deduced prices for newly built vessels in 2007 (US$ millions);
Crude oil tanker	200,000+ dwt	87
Crude oil tanker	120,000–199,999 dwt	59
Crude oil tanker	80,000–119,999 dwt	47
Crude oil tanker	60,000–79,999 dwt	41
LPG tanker	50,000+ m^3	63
LNG tanker	200,000+ m^3	168
LNG tanker	0–199,999 m^3	105
Bulk carrier	200,000+ dwt	149
Bulk carrier	100,000–199,999 dwt	60
Bulk carrier	60,000–99,999 dwt	37
Container vessel	8,000+ TEU	120
Container vessel	5,000–7,999 TEU	104
Container vessel	3,000–4,999 TEU	91
Container vessel	2,000–2,999 TEU	46

Table A4.10 *Approximate cost efficiency and maximum abatement potential of an air-cavity system (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–115	–90	7.5	0.9%
	High reduction potential	–150	–140	24.4	1.9%

estimation methods that were applied and the respective outcomes. We will finally present the emanating cost efficiency and the maximum abatement potential. Note that the results have to be considered not as a precise calculation but rather as a rough estimation, due to the lack of data.

A4.43 The starting point of the estimation of the incremental costs of the coatings, in comparison to regular TBT-free coating, is the cost data given for a Panamax bulker. These costs can be estimated to lie in a range of US$43,000 to US$51,600 for coating 1 and in a range of US$221,000 to US$265,200 for coating 2.

A4.44 We assume that the incremental costs vary between the different ship categories, since these differ in the size of the hull surface to be treated. To make an estimation of the incremental costs that have to be incurred by the different ship categories, we applied a cost factor to the costs given for the Panamax bulker, based on the gross tonnage of the different ship categories. This cost factor is $\frac{(\text{Gross Tonnage}_{\text{Ship } i})^{2/3}}{(\text{Gross Tonnage}_{\text{Panamax bulker}})^{2/3}}$, thus making the simplifying assumption that the hull surface to be painted is proportional to the ⅔-power of the gross tonnage of the ship and that the incremental costs vary linearly with this estimated surface. The resulting ranges of incremental costs for the different ship categories are given in Table A4.11.

A4.45 For the calculation of the cost efficiency, we assumed that the estimated costs have to be borne every five years to be able to gain the fuel/emission benefit as specified below. For simplicity, we use one cost figure for retrofitting and non-retrofitting of the coating.

A4.46 The starting point of the estimation of the incremental benefits, in comparison to regular TBT-free coating, is again the data given for a Panamax bulker. These incremental fuel/CO_2 savings can be estimated to lie in a range of 0.5–2% for coating 1 and in a range of 1–5% for coating 2.

Table A4.11 *Estimated approximate incremental costs (US$) for two different hull coatings in comparison to regular TBT-free coating*

		Coating 1		Coating 2	
		Low cost estimate	High cost estimate	Low cost estimate	High cost estimate
Crude oil tanker	200,000+ dwt	115,000	140,000	600,000	720,000
	120,000–199,999 dwt	75,000	85,000	380,000	455,000
	80,000–119,999 dwt	55,000	65,000	275,000	330,000
	60,000–79,999 dwt	40,000	50,000	220,000	260,000
	10,000–59,999 dwt	25,000	30,000	135,000	165,000
	0–9,999 dwt	7,500	8,500	35,000	45,000
Product tanker	60,000+ dwt	50,000	60,000	250,000	300,000
	20,000–59,999 dwt	35,000	40,000	170,000	205,000
	10,000–19,999 dwt	20,000	25,000	115,000	135,000
	5,000–9,999 dwt	20,000	20,000	95,000	110,000
	0–4,999 dwt	15,000	20,000	80,000	95,000
Chemical tanker	20,000+ dwt	35,000	40,000	170,000	205,000
	10,00–19,999 dwt	20,000	25,000	115,000	135,000
	5,000–9,999 dwt	20,000	20,000	95,000	110,000
	0–4,999 dwt	15,000	20,000	80,000	95,000
LPG tanker	50,000+ cbm	45,000	55,000	235,000	285,000
	0–49,999 cbm	10,000	10,000	55,000	65,000
LNG tanker	200,000+ cbm	80,000	95,000	420,000	505,000
	0–199,999 cbm	60,000	70,000	305,000	365,000
Other tanker	Other	10,000	15,000	60,000	70,000
Bulk carrier	200,000+ dwt	85,000	100,000	435,000	520,000
	100,000–199,999 dwt	70,000	85,000	360,000	430,000
	60,000–99,999 dwt	50,000	55,000	250,000	295,000
	35,000–59,999 dwt	35,000	45,000	185,000	225,000
	10,000–34,999 dwt	25,000	30,000	135,000	160,000
	0–9,999 dwt	15,000	20,000	85,000	105,000
General cargo	10,000+ dwt	25,000	30,000	130,000	155,000
	5,000–9,999 dwt	9,500	10,000	50,000	60,000
	0–4,999 dwt	4,500	5,500	25,000	30,000
General cargo	10,000+ dwt, 100+ TEU	25,000	30,000	135,000	165,000
	5,000–9,999 dwt, 100+ TEU	10,000	10,000	50,000	60,000
	0–4,999 dwt, 100+ TEU	5,000	6,000	25,000	30,000
Other dry bulk carrier	Reefer	10,000	15,000	55,000	65,000
	Special	10,000	15,000	65,000	75,000
Unitized container vessel	8,000+ TEU	85,000	105,000	445,000	535,000
	5,000–7,999 TEU	60,000	75,000	315,000	375,000
	3,000–4,999 TEU	45,000	50,000	225,000	275,000
	2,000–2,999 TEU	30,000	40,000	165,000	200,000
	1,000–1,999 TEU	25,000	25,000	120,000	140,000
	0–999 TEU	10,000	15,000	55,000	70,000
Unitized vehicle carrier	4,000+ ceu	50,000	60,000	270,000	320,000
	0–3,999 ceu	25,000	30,000	130,000	155,000
Ro-Ro vessel	2,000+ lm	50,000	60,000	255,000	305,000
	0–1,999 lm	15,000	20,000	80,000	95,000

Table A4.11 *Continued*

		Coating 1		Coating 2	
		Low cost estimate	High cost estimate	Low cost estimate	High cost estimate
Ferry	Pax only, 25kn+	45,000	55,000	235,000	280,000
	Pax only, <25kn	10,000	10,000	50,000	60,000
	RoPax, 25kn+	35,000	40,000	175,000	210,000
	RoPax, <25kn	15,000	20,000	85,000	100,000
Cruise ship	100,000+ gt	115,000	135,000	580,000	695,000
	60,000–99,999 gt	70,000	85,000	360,000	435,000
	10,000–59,999 gt	40,000	50,000	210,000	250,000
	2,000–9,999 gt	10,000	15,000	65,000	75,000
	0–1,999 gt	4,000	4,500	20,000	25,000

A4.47 We assume that these benefits differ between the different ship types. To make the distinction of the different fuel savings per ship type, we make use of the fuel savings that are guaranteed by one manufacturer in the initial period for one of its coatings. Assigning the difference between the ship types given there to the range of fuel saving given for the Panamax bulker, we come to the ranges of incremental fuel savings as given in Table A4.12.

Table A4.12 *Approximate incremental fuel reduction potential per ship type*

	Coating 1		Coating 2	
	Low estimate (%)	High estimate (%)	Low estimate (%)	High estimate (%)
Crude oil tanker	0.7	2.9	1.5	7.3
Product tanker	0.6	2.4	1.2	6.1
Chemical tanker	0.6	2.4	1.2	6.1
LPG tanker	0.4	1.7	0.9	4.3
LNG tanker	0.4	1.7	0.9	4.3
Other tanker	0.4	1.6	0.8	4.1
Bulk carrier	0.5	2.0	1.0	5.0
General cargo	0.5	2.0	1.0	5.0
Other dry bulk carrier	0.4	1.6	0.8	4.1
Unitized container vessel	0.6	2.2	1.1	5.5
Unitized vehicle carrier	0.4	1.6	0.8	4.1
Ro-Ro vessel	0.4	1.6	0.8	4.1
Ferry	0.4	1.6	0.8	4.1
Cruise ship	0.4	1.6	0.8	4.1

A4.48 As to the applicability, we assume that both kinds of coating can be used by every ship type. Retrofitting is assumed to be possible.

A4.49 Given the data, and the simplifying assumptions that are specified above, the cost efficiency and the maximum abatement potential of the two different types of coatings turn out to be as given in Tables A4.13 and A4.14.

A4.50 In the following we will briefly present the other measures, in the order of the grouping mentioned above. For several measures, the cost data will not be given explicitly. The data for these measures were taken from Wärtsilä (2008) [7]. In this brochure, the reduction potential and the payback time of different measures are specified. Assuming that the price of bunker fuel underlying these data is US$300/tonne, and making use of the IMO fuel consumption data of the fleet in 2007, we derived the corresponding costs of the measures for the different ship types. Since the reduction potential and the payback time are not

Table A4.13 *Approximate cost efficiency and maximum abatement potential of hull coating 1 (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–115	–105	6.6	0.50%
	High reduction potential	–150	–150	26.1	2.10%

Table A4.14 *Approximate cost efficiency and maximum abatement potential of hull coating 2 (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–40	–15	13.2	1.10%
	High reduction potential	–140	–130	65.3	5.20%

differentiated with respect to ship types, whereas fuel consumption is, the costs for a measure differ per ship type. In Table A4.15 you find these measures, the respective average reduction potentials and the payback times that were used in our calculation. You find the lifetime/the frequency of the investment that were assumed in the third column. As to the other measures, the data are, if not otherwise mentioned, based on an expert assessment by the consortium.

Table A4.15 *Approximate average reduction potential and payback time for cost calculation of measures, taken from Wärtsilä (2008) [7]*

Measure	Average reduction potential	Payback time (years)	Lifetime/frequency of investment
Autopilot upgrade/adjustment	1.75%	0.5	10
Common rail upgrade	0.30%	5	10
Low-energy/low-heat lighting	0.45%	10	10
Main engine tuning	0.45%	10	10
Propeller brushing	3.50%	0.5	1
Propeller performance monitoring	2.25%	0.5	10
Propeller/rudder upgrade	4.00%	10	10
Propeller upgrade (winglet, nozzle)	2.50%	10	10
Speed control pumps and fans	0.60%	10	10
Power management (newbuilds only)	2.25%	10	30
Transverse thruster opening (flow optimization, grids)	3.00%	0.5	10

PROPELLER MAINTENANCE

Propeller performance monitoring

Table A4.16 *Approximate cost efficiency and maximum abatement potential for propeller performance monitoring (price of bunker fuel is US$500/tonne, interest rate is 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–135	–130	5.4	0.4%
	High reduction potential	–160	–160	42.5	3.4%

Increased frequency of propeller brushing

A4.51 Assumptions:

1. Low cost estimate: US$3,000, high cost estimate: US$4,500;
2. Costs data apply to 5-year period;
3. Costs are the same for every ship type;
4. Low reduction potential: 0.5%, high reduction potential: 3%; and
5. All vessel types can make use of the measure.

Table A4.17 *Approximate cost efficiency and maximum abatement potential for an increased frequency of propeller brushing (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–160	–130	6.2	0.50%
	High reduction potential	–160	–160	36.7	2.90%

Propeller brushing

Table A4.18 *Approximate cost efficiency and maximum abatement potential for propeller brushing (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–75	–65	25.4	2.00%
	High reduction potential	–125	–120	62.8	5.00%

PROPELLER/PROPULSION SYSTEM UPGRADES

Propeller/rudder upgrade

Table A4.19 *Approximate cost efficiency and maximum abatement potential for propeller/rudder upgrade (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	90	120	19.7	1.60%
	High reduction potential	–80	–70	58.5	4.70%

Propeller upgrade (winglet, nozzle)

Table A4.20 *Approximate cost efficiency and maximum abatement potential for propeller upgrade (various) (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	530	600	1.3	0.10%
	High reduction potential	–90	–80	11.2	0.90%

Propeller boss cap fin

A4.52 Assumptions:

1. Capital costs: US$20,000 for 735 kW engine to US$146,000 for 22,050 kW engine (Frey and Kuo, 2007) [4];
2. Linear relationship between kW of main engine and price;
3. No recurring costs;
4. Reduction potential: 4–5%;
5. Expected lifetime: 10 years; and
6. All vessels can make use of it.

Table A4.21 *Approximate cost efficiency and maximum abatement potential for a propeller boss cap fin (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–155	–150	42.9	3.40%
	High reduction potential	–155	–155	53.1	4.20%

HULL COATING AND MAINTENANCE

Hull performance monitoring

A4.53 Assumptions:

1. Non-recurring costs: US$45,000 (every 5 years);
2. Annual operating costs: US$5,000;
3. Costs are the same for every ship type; and
4. Reduction potential: 0.5–5%.

Table A4.22 *Approximate cost efficiency and maximum abatement potential for hull performance monitoring (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–45	–45	6.2	0.50%
	High reduction potential	–150	–150	61.2	4.90%

Hull brushing

A4.54 Assumptions:

1. Low cost estimate: US$26,000; High cost estimate: US$39,000;
2. Brushing is being done every five years;
3. To differentiate costs between ship types, the same cost factor is being applied as for the hull coating measures;
4. 1–10% reduction potential;
5. Can be applied to all ship types.

Table A4.23 *Approximate cost efficiency and maximum abatement potential for hull brushing (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–95	–65	12.7	1.00%
	High reduction potential	–155	–150	125.6	10.00%

Underwater hull hydroblasting

A4.55 Assumptions:

1. Low cost estimate: US$33,000; High cost estimate: US$49,500;
2. Brushing is being done every 5 years;
3. To differentiate costs between ship types, the same cost factor is being applied as for the hull coating measures;
4. 1–10% reduction potential; and
5. Can be applied to all ship types.

Table A4.24 *Approximate cost efficiency and maximum abatement potential for underwater hydroblasting (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–80	–35	12.7	1.00%
	High reduction potential	–155	–150	125.6	10.00%

A4.56 Assumptions:

1. Low cost estimate: US$68,000; High cost estimate: US$81,600;
2. To differentiate costs between ship types, the same cost factor is being applied as for the hull coating measures;
3. 5–10% reduction potential; and
4. A full blast, instead of a spot blast, is applied once to old ships to restore their condition (assumed to be vessels at the age of 25 years).

Table A4.25 *Approximate cost efficiency and maximum abatement potential for dry-dock full blast (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–155	–150	8.2	0.60%
	High reduction potential	–160	–160	16.1	1.30%

VOYAGE AND OPERATIONS OPTIONS

Performance monitoring: shaft power meter

A4.57 Assumptions:

1. Low cost estimate: US$26,000; High cost estimate: US$31,200 (purchase costs of meter);

2. Costs are the same for every ship type;
3. Expected lifetime of a meter is 10 years;
4. 0.5–2% reduction potential;
5. Benefit is due to optimization of ballast, load and trim; and
6. Can be applied to all ship types.

Table A4.26 *Approximate cost efficiency and maximum abatement potential for a shaft power meter (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	70	115	5.4	0.40%
	High reduction potential	–105	–95	21.3	1.70%

Performance monitoring: fuel consumption meter

A4.58 Assumptions:

1. Low cost estimate: US$46,000; High cost estimate: US$55,200 (purchase costs for a meter);
2. Costs are the same for every ship type;
3. Expected lifetime of a meter is 10 years;
4. 0.5–2% reduction potential;
5. Benefit is due to optimization of ballast, load and trim; and
6. Can be applied to all ship types.

Table A4.27 *Approximate cost efficiency and maximum abatement potential for a fuel consumption meter (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	245	330	5.4	0.40%
	High reduction potential	–60	–40	21.3	1.70%

Weather routeing

A4.59 Assumptions:

1. Low cost estimate: US$800 p.a.; High cost estimate: US$1,600 p.a.;
2. 0.1–4% reduction potential; and
3. Applied by ocean-going vessels that have route flexibility/not applied by ferries and cruise ships.

Table A4.28 *Approximate cost efficiency and maximum abatement potential for weather routeing (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–130	–100	1.2	0.10%
	High reduction potential	–165	–160	46	3.70%

Autopilot upgrade/adjustment

Table A4.29 *Approximate cost efficiency and maximum abatement potential for autopilot upgrade/adjustment (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–140	–140	5.4	0.40%
	High reduction potential	–160	–160	31.9	2.50%

MAIN ENGINE RETROFIT MEASURES

Common rail upgrade

Table A4.30 *Approximate cost efficiency and maximum abatement potential for a common rail upgrade (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	25	45	1.1	0.10%
	High reduction potential	–125	–120	5.3	0.40%

Main engine tuning

Table A4.31 *Approximate cost efficiency and maximum abatement potential for main engine tuning (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	405	470	1.0	0.10%
	High reduction potential	–90	–85	7.8	0.60%

RETROFIT HULL IMPROVEMENTS

Transverse thruster opening (flow optimization, grids)

Table A4.32 *Approximate cost efficiency and maximum abatement potential for transverse thruster openings (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	–145	–140	10.7	0.9%
	High reduction potential	–160	–160	53.1	4.2%

AUXILIARY SYSTEMS

Low-energy/low-heat lighting

Table A4.33 *Approximate cost efficiency and maximum abatement potential for low-energy/low-heat lighting (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	385	440	0.1	0.0%
	High reduction potential	–95	–85	0.6	0.0%

Speed control pumps and fans

Table A4.34 *Approximate cost efficiency and maximum abatement potential for speed control pumps and fans (price of bunker fuel is US$500/tonne, interest rate 4%)*

		Cost efficiency (US$/tonne of CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	210	250	2.1	0.2%
	High reduction potential	–90	–80	10.6	0.8%

Power management

Table A4.35 *Approximate cost efficiency and maximum abatement potential for power management (price of bunker fuel is US$500 /tonne, interest rate 4%)*

		Cost efficiency (US$/tonne CO_2)		Maximum abatement potential	
		Low cost estimate	High cost estimate	in Mt	% of total emissions
2020	Low reduction potential	100	130	0.1	0.0%
	High reduction potential	–130	–125	0.7	0.1%

REFERENCES

1 AEA (2008), Greenhouse gas emissions from shipping: trends, projections and abatement potential, Final report.
2 Corbett, J.J., Wang, C. and Firestone, J. (2006), Estimation, Validation, and Forecasts of Regional Commercial Vessel Inventories, Tasks 1 and 2: Baseline Inventory and Ports Comparison, Final Report.
3 De Nederlandsche Bank, Rendement 10-jaars staatsleningen eurogebied, VS en Japan, http://www.statistics.dnb.nl/index.cgi?lang=nl&todo=Rentes, (Accessed: 15 December 2008).
4 Frey, H.C. and Kuo, P.-Y. (2007) Best practices guidebook for greenhouse gas reductions in freight transportation. Report prepared for U.S. Department of Transportation.
5 IMO (2008), Updated Study on Greenhouse Gas Emissions from Ships, Phase 1 Report, 1 September 2008.
6 UNCTAD (2008), Review of Maritime Transport.
7 Wärtsilä (2008), Boosting energy efficiency, Energy efficiency catalogue.

Appendix 5

The Steering Committee for the Second IMO GHG Study 2009

A5.1 In accordance with the Terms of Reference for the update of the 2000 IMO GHG Study, which was adopted in July 2007 by the fifty-sixth session of IMO's Marine Environment Protection Committee, a Steering Committee was established to oversee the work. The Secretary-General invited 19 Member States to designate representatives to the Steering Committee and all of them responded positively. The Steering Committee met seven times since its establishment in December 2007. It provided input to the tendering process, approved the study outline, monitored the progress of the study and reported on the progress to the Marine Environment Protection Committee. The Steering Committee also provided general oversight to the authors, reviewed preliminary drafts of the two reports (Phase 1 and 2) and provided comments to assist the Consortium in its work.

A5.2 The Steering Committee met on 6 April 2009 for its final meeting to consider the final draft report and whether or not it complied with the Terms of Reference as adopted by the fifty-sixth session of the Marine Environment Protection Committee. The Steering Committee agreed that the final draft report satisfied the Terms of Reference and unanimously accepted it, recognizing that the responsibility for the scientific content of the Study would rest with the Consortium.

A5.3 The Steering Committee reported on the progress to the Marine Environment Protection Committee's fifty-seventh (MEPC 57/4/18 and MEPC 57/4/18/Add.1) and fifty-eighth (MEPC 58/4/2) sessions and submitted a final status report to the fifty-ninth session (MEPC 59/4/4).

A5.4 The Steering Committee had the following composition:

CHAIRPERSON

Ms. Petra Bethge, First Secretary (Transport), Embassy of the Federal Republic of Germany, London

VICE-CHAIRMAN

Mr. Bin Okamura, Adviser, Japan Ship Technology Research Association

MEMBERS

Dr. Linda Rasmussen, Senior Policy Adviser, Transport, Regional Development and Local Government, Australia

Mr. Greg Bates, Counsellor, Canadian High Commission, London

Mr. Zhang Renping, First Secretary (Maritime), Embassy of the People's Republic of China, London

Mr. Jesper Loldrup, Permanent Representative of Denmark to the International Maritime Organization, Royal Danish Embassy, London

Capt. Efthimios Liberopoulos, Maritime Attaché, Embassy of Greece, London

Mr. Madhav Chandra, Minister (Political), High Commission for India, London

Mr. Ali Marzban, Deputy Permanent Representative of the Islamic Republic of Iran to the International Maritime Organization

Mr. Ichiro Shimizu, Counsellor (Transport), Embassy of Japan, London

Captain David Bruce, Permanent Representative of the Republic of the Marshall Islands to the International Maritime Organization

Mr. William Azuh, Maritime Attaché, Alternate Permanent Representative of Nigeria to the International Maritime Organization, High Commission for the Federal Republic of Nigeria, London

Moisés de Gracia, Technical Adviser, Permanent Mission of Panamá to the International Maritime Organization

Mr. Neil Frank R. Ferrer, First Secretary and Consul, Alternate Permanent Representative to the International Maritime Organization, Embassy of the Philippines, London

Mr Ki-tack Lim, Minister-Counsellor (Maritime), Embassy of the Republic of Korea, London

Mr. Alexander Y. Frolov, Permanent Representative of the Russian Federation to the International Maritime Organization, Permanent Mission of the Russian Federation to the International Maritime Organization

Mr. Dumisani Theophilus Ntuli, Minister (Maritime Affairs), Alternate Permanent Representative of the Republic of South Africa to the International Maritime Organization, High Commission for the Republic of South Africa, London

Mr. David Kimball, Policy Advisor, Department for Transport, the United Kingdom

Mr. Jock Whittlesey, Counsellor for Environment, Science and Technology, Permanent Representative of the United States of America to the International Maritime Organization, American Embassy, London

Mr. Laurent Parenté, Permanent Representative of Vanuatu to the International Maritime Organization

UN ADVISORS

Ms. Martina Otto, Head, Policy Unit – Energy Branch – Division of Technology, Industry and Economics, UNEP

Mr. Fernando Castellanos Silveira, Associate Programme Officer, Analysis and Methods, Adaptation, Technology and Science Programme, UNFCCC

IMO STAFF

Mr. Miguel Palomares, Director, Marine Environment Division

Mr. Eivind S. Vagslid, Head, Chemical and Air Pollution Prevention Section, Marine Environment Division

Ms. Sabine Knapp, Statistical Officer, Office of the Secretary-General

Ms. Lucy Essuman, Principal Secretary, Marine Environment Division

Mr. Brian Starkey, Proofreader, Marine Environment Division