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REDUCTION OF GHG EMISSIONS FROM SHIPS

Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures

Submitted by the Institute of Marine Engineering, Science and Technology (IMarEST)

SUMMARY

Executive summary:	This information document updates a study on the economics and cost effectiveness of technical and operational measures to reduce CO_2 emissions from ships. The methodologies and analyses are structured to support the development and implementation of any regulatory and/or corporate policies that may be adopted. The results may be used by ship designers, builders, owners and operators as a tool in their decision-making on whether to employ one or more technologies or operational measures. The methodology and inputs are structured such that each can be varied should new information be incorporated or to posit and test different views on any of the assumptions.
Strategic direction:	7.3
High-level action:	7.3.2
Planned output:	7.3.2.1
Action to be taken:	Paragraph 6
Related documents:	MEPC 62/5/2, MEPC 61/5/7, MEPC 61/INF.18 and MEPC 59/INF.10

Introduction

1 The Marine Environment Protection Committee (MEPC) commissioned a study of greenhouse gas emissions (GHG) from ships, first published in 2000, updated in 2009 as the Second IMO GHG Study 2009, and presented it at MEPC 59. The Second IMO GHG Study 2009 shows the social costs of some existing technical and operational measures.

2 The Technical and Research Committee (T&R) of the Society of Naval Architects and Marine Engineers (SNAME), in cooperation with the Institute of Marine Engineering, Science and Technology (IMarEST), conducted an in-depth analysis of the cost-effectiveness and CO_2 emission reductions potential of technical and operational measures.

3 After the submission of an earlier version of the report to MEPC 61 (MEPC 61/5/7 and MEPC 61/INF.18), the project team identified some parts that required updating, and revised the final results and the report accordingly. All graphs, tables, and supplementary

information in the chapters, appendices, and online materials have been updated. Significant changes were made to the speed reduction analyses in particular. Two measures have been analysed: a 10% speed reduction and a 20% speed reduction. Although both have negative abatement costs (i.e. at a net cost savings) at projected fuel prices, the cost-effectiveness of a 10% speed reduction is superior to a 20% speed reduction. Therefore, for most ship types a 10% speed reduction has been included in the marginal abatement cost curves, which resulted in a smaller abatement potential than previously published. It should be noted, however, that this study did not evaluate the optimal speed reduction. Most likely the speed reductions with the optimal cost-effectiveness lie between 10% and 20% for most ship types, so that the presented abatement potential of this option is an underestimation.

4 This report had two primary purposes. The first was to develop a standardized methodology for examining measures to improve the energy efficiency of ships. The methodology was designed to estimate the cost-effectiveness and the potential of each measure to achieve CO_2 emission reductions. The second objective of this study was to apply the methodology to the 22 abatement measures for which data were available. The data on the cost, reliability, variability, and effectiveness of each abatement measure were obtained from published sources, including both equipment manufacturers and other studies. The study attempted to corroborate the data by directly interviewing operators and others with experience with the measures. This analysis provided estimates of the potential for CO_2 emission reductions and associated marginal abatement costs for 14 types of new and existing ships, as defined by the Second IMO GHG Study 2009. For each vessel type, size, and age, these cost estimates were plotted against estimated potential CO_2 emission reductions, and the marginal abatement cost curves (MACC) for each ship type were presented. Sensitivity analyses were also performed to examine the impact of fuel prices and discount rates on the cost effectiveness of the measures. Key findings should be of interest to policy-makers, ship owners and operators, and other interested parties.

5 Further work needs to be done on the actual in-service cost, reliability, variability, and effectiveness of these measures. SNAME's Technical & Research Committee will continue to evaluate these measures.

Action requested of the Committee

6 The Committee is invited to note the report in the annex.

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ANNEX

MARGINAL ABATEMENT COSTS AND COST EFFECTIVENESS OF ENERGY-EFFICIENCY MEASURES

25 March 2011

Prepared by

**THE SOCIETY OF NAVAL ARCHITECTS AND MARINE ENGINEERS (SNAME)
TECHNICAL AND RESEARCH PROGRAM
PANEL AHP 20: GREENHOUSE GASES AND ECONOMICS**

Mr. Bruce A. Russell, Chairman Mr. David St Amand, Co-Chairman

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PREFACE

In February 2010 the Society of Naval Architects and Marine Engineers (SNAME) and the Marine Board of the National Academies' Transportation Research Board (TRB) convened a symposium: ***Climate Change and Ships: Increasing Energy Efficiency***. Over ninety individuals attended from the shipping industry and related service industry, marine engineering and naval architectural firms, product manufacturers, government, research institutions and organizations and non-governmental organizations. A major recommendation of the symposium was to "conduct an analysis of the marginal abatement costs for vessel owners and operators to employ technologies or operational measures to increase a vessel's energy efficiency and reduce its CO_2 emissions..." such a project should "address the direct costs of mitigation measures and opportunity costs of mitigation." Previously, SNAME had established an ad hoc panel (AHP 20): Greenhouse Gases and Economics and selected that group to conduct this analysis, with funding or in-kind contributions from the International Council on Clean Transportation (ICCT), CE Delft and SNAME, Navigistics Consulting, and JS&A Environmental Services, Inc.

After the submission (IMO MEPC 61/5/7 and MEPC 61/INF.18), the project team identified a number of places that required updating, and revised the final results and the report accordingly. All graphs, tables, and supplementary information in the chapters, appendices, and online materials have been updated. Significant changes were made for the speed reduction analyses in particular. Two measures have been analysed: a 10% speed reduction and a 20% speed reduction. Although both have negative abatement costs (i.e., at a net cost savings) at projected fuel prices, the cost-effectiveness of a 10% speed reduction is superior to a 20% speed reduction. Therefore, for most ship types a 10% speed reduction has been included in the marginal abatement cost curves, which resulted in a smaller abatement potential than previously published. It should be noted however that this study did not evaluate the *optimal* speed reduction. Most likely, the speed reductions with the optimal cost-effectiveness lie between 10% and 20% for most ship types, so that the presented abatement potential of this option is underestimated.

Policy makers and stakeholders have identified a range of abatement measures that are available or under development to slow the growth of energy consumption and CO_2 emissions from maritime shipping. However the full cost accounting and assessment of effectiveness has been sparse. The cost-effectiveness of individual measures and of sets of measures is of increasing interest to policy makers, ship designers and builders, and existing ship owners (Buhaug et al. 2009). Moreover, a Marginal Abatement Cost Curve (MACC) showing the cost effectiveness of sets of measures can assist policy makers in assessing the impacts of policy instruments. Understanding these costs is of critical importance to both develop energy efficiency standards for new and existing ships and to forecast the impact under ship-based CO_2 reduction requirements / energy efficiency standards. One of the most significant challenges in undertaking these tasks is the lack of data. To develop robust and accurate models, detailed ship cost effectiveness data and technical/operational data are needed. The data include, but are not limited to, the fixed costs and operating costs per ship; the energy-efficiency improvement potential of technologies and operational measures; the costs of implementing technologies and improving operational measures; and the costs of collecting information.

The main objectives of the analysis and this report were to: 1) develop a comprehensive and transparent methodology to estimate the cost-effectiveness of individual fuel efficiency improvement measures; 2) identify barriers to implementing measures; 3) identify and assess the cost effectiveness of individual measures where data are available and the applicability to the various ship types and sizes for both new and existing ships, taking into account the uncertainties with respect to both cost and abatement potential; 4) develop a method for estimating the MACC for each vessel type based on the cost-effectiveness analysis, and to 5) estimate the MACC for the world fleet and for different vessel types for the years 2020 and 2030 under different implementation scenarios. Sensitivity analyses were also performed to examine the impact of fuel price and discount rates.

It should be noted that data for this study on the abatement measures was obtained from published sources including both manufacturers and other studies. We attempted to corroborate this data with direct interviews of operators and others with experience with the measures. However, further work needs to be done on the actual in-service cost, reliability, variability, and effectiveness of these measures. SNAME's Technical & Research Committee will continue to evaluate these measures.

LIST OF ABBREVIATIONS

ACS	Air Cavity System
BAU	Business as Usual
CAPM	Capital Asset Pricing Model
CGT	Compensated Gross Tonnage
CO_2	Carbon Dioxide
COA	Contract of Affreightment
DWT	Deadweight Tonnage
EEDI	Energy Efficiency Design Index
EEOI	Energy Efficiency Operational Indicator
ECA	Emission Control Area
EIA	U.S. Energy Information Administration
GHG	Greenhouse Gas
GT	Gross Tonnage
HVAC	Heating, Ventilation and Air Conditioning
HFO	Heavy Fuel Oil
LOA	Length Overall
LNG	Liquefied Natural Gas
MAC	Marginal Abatement Cost
MACC	Marginal Abatement Cost Curve
MCR	Maximum Continuous Rating
NASA	National Aeronautics and Space Administration
OCIMF	Oil Companies International Marine Forum
ROE	Expected Return on Equity
SECA	Sulphur Emission Control Area
SEEMP	Ship Energy Efficiency Management Plan
UNCTAD	United Nation Conference on Trade and Development
WACC	Weighted Average Cost of Capital
WHR	Waste Heat Recovery
WTI	West Texas Intermediate

CONTENTS

CHAPTER 1

EXECUTIVE SUMMARY

1.1 This report had two primary purposes. The first was to develop a standardized methodology for examining energy-efficiency improvement measures on ships. The methodology was designed to estimate the cost-effectiveness and CO_2 emissions reduction potential of each measure. The second objective of this report was to apply the methodology to the twenty-two (22) abatement measures for which data was available. The data on the cost, reliability, variability, and effectiveness of each abatement measure was obtained from published sources including both manufacturers and other studies. We attempted to corroborate this data with direct interviews of operators and others with experience with the measures. However, further work needs to be done on the actual in-service cost, reliability, variability, and effectiveness of these measures. SNAME's Technical & Research Committee will continue to evaluate these measures. This analysis provided estimates of CO_2 emissions reduction potential and associated marginal abatement costs for 14 types of new and existing ships as defined by the IMO GHG Experts Group. For each vessel type, size, and age, these cost estimates were plotted against estimated CO_2 emissions reduction potential and the marginal abatement cost curves for each ship type were presented. Sensitivity analyses were also performed to examine the impact of fuel prices and discount rates on the cost effectiveness of the measures. To avoid complexity, all costs are in USD$; and emission reductions are in metric tonnes CO_2. This study did not assume that ship owners and operators would make the investments or employ the specific operational measures, but just demonstrated what the estimated costs and benefits would be if the necessary investment(s) were made. The report strives to present these estimates in an accessible format. Key findings should be of interest to policy makers, ship owners and operators, and other interested parties.

1.2 After the submission (IMO MEPC 61/5/7 and MEPC 61/INF.18), the project team identified a number of places that required updating, and revised the final results and the report accordingly. All graphs, tables, and supplementary information in the chapters, appendices, and online materials have been updated. Significant changes were made for the speed reduction analyses in particular. Two measures have been analysed: a 10% speed reduction and a 20% speed reduction. Although both have negative abatement costs at projected fuel prices, the cost-effectiveness of a 10% speed reduction is superior to a 20% speed reduction. Therefore, for most ship types a 10% speed reduction has been included in the marginal abatement cost curves, which resulted in a smaller abatement potential than previously published. It should be noted however that this study did not evaluate the *optimal* speed reduction. Most likely, the speed reductions with the optimal cost-effectiveness lie between 10% and 20% for most ship types, so that the presented abatement potential of this option is underestimated

Methodology

1.3 This report describes fifty (50) technical and operational energy-efficiency improvement measures and presents a detailed analysis of twenty-two (22) of these measures for which we could obtain data. The analysis includes an assessment of the cost effectiveness and abatement potential of each measure (often presented as a range). The applicability of each measure was determined for new and existing vessels and fourteen (14) ship types by size and age (a total of three hundred eighteen (318) combinations). Implementation barriers and strategies to address these barriers are described in this report. A basis for projecting and applying the learning rate for new technologies was developed and used in future cost estimates The measures were grouped (fifteen (15) groups) to ensure that similar measures were identified as mutually exclusive so as not to overestimate the energy-efficiency improvement potentials of employing multiple measures.

1.4 For each measure and for each vessel type by size and by age, where the measure is appropriate, low and high estimates of the cost-effectiveness to employ the measure were estimated. The range of estimates reflects different operating patterns of vessels and uncertainty about the cost and abatement potential of individual measures. These estimates of cost effectiveness are for a high emissions reduction potential and a low emissions reduction potential. For each reduction potential, there is one high cost estimate and one low cost estimate. The low and high reduction potentials are associated with the ranges and uncertainty of both the cost effectiveness and the energy-efficiency improvement potential for each measure. Appendix III contains marginal abatement cost estimates for ships as a function of ship type, size and age. The methods and assumptions to estimate the cost effectiveness were described in detail. Key factors about each measure were analyzed, as well as implementation decision making by the ship owner or operator including but not limited to cost effectiveness, capital and opportunity costs, pay-back periods, and discount and freight rates.

1.5 In turn, marginal abatement costs curves (MACC), resulting from the analysis are presented in this report for new construction for the fourteen ship types. The MACC plots marginal abatement costs against CO_2 emissions reductions. These MACC were based on a rank ordering of the measures or group of measures based on the cost effectiveness and the appropriateness of the measure to a specific ship type and size, including impact on percent (%) emissions reduction, ease of implementation, and other factors. The cost-effectiveness of individual measures was summed to develop marginal abatement cost curves. These MACC are graphically presented in this report with high, central and low estimates for the fourteen ship types. One partial set of MACC is in Appendix V. The complete data and findings for each measure including, estimated cost effectiveness and potential CO_2 emissions reduction that comprise these MACC are available at http://www.sname.org/SNAME/climatechange/MACreport and http://www.theicct.org/programs/Marine. The specific measures which make up each MACC estimate are identified.

1.6 The cost effectiveness and the estimates of CO_2 emissions reduction potential for each measure vary widely as a function of ship type, size, and age. We depict this by providing low and high estimates. A range is given because of the uncertainty with respect to the costs and abatement potential. The aggregation of these costs when estimating the net abatement potential using marginal abatement curves similarly shows that the costs and abatement potential vary widely among types of ships. In particular, when aggregating cost effectiveness estimates for measures to develop MACC curves, analysts should be attentive to the impact that certain measures have by ship types that impacts the net costs and potential of efficiency improvements. For example, speed reductions for containerships have a greater potential for emissions reduction relative to slower moving vessels and most other measures.

Key Findings

1.7 The cost effectiveness analysis examined both new and existing ships. One of the most striking findings is that the MACC for 2020 and 2030 show a considerable abatement potential at negative costs: meaning that many of these measures are profitable (i.e., show a positive net present value) on both new and existing ships. This finding is consistent with other MACC studies for maritime transport, though this study also looked at existing ships and is also consistent with current industry practice (i.e., implementation on existing ships). The interpretation of these findings requires careful consideration. First, considerable cost savings and CO_2 emissions reduction can accrue now and through 2020 and beyond for existing ships. Second, the meaning of this finding is that by 2020 and 2030, the energy-efficiency of the world fleet may be improved considerably while lowering transport costs, assuming that fuel prices will continue to rise in real terms and that demand for maritime transport will continue to grow. And third, of the 50 measures identified we were only able to analyze 22 as we had insufficient data to assess other measures.

1.8 Net abatement costs and the corresponding CO_2 reduction potential are highly dependent on speed reduction as a measure. For example, when speed reductions are eliminated as a design option[1] for containerships in 2020, the central estimate for CO_2 emissions reduction potential is almost 24% less when it is included at the same net marginal abatement costs of less than zero or more simply at a cost savings or no net cost. Similar, though not as dramatic results (both in absolute and relative terms) are expected from most other ship types.

1.9 Operational abatement measures have a significant potential to reduce emissions, as do technical measures. As noted, speed reduction accounts for a significant proportion of many of the estimated operational CO_2 emissions reductions. For new-build ships, speed reduction is assumed to be achieved, in order to obtain "EEDI credit," through the design and installation of lower powered main propulsion and, therefore, is considered a "design" measure (referred to as an "EEDI related" measure as opposed to an "operational" related measure, for "new-build" ships. We infer from our analyses that speed reduction (through smaller engines for new ships and speed reductions for ships in service) can account for a significant proportion of cost–effective increased energy-efficiency.

1.10 Of the 22 measures we analyzed, several have limited potential application to certain ship types and others may not be appropriate for existing ships. The potential cost effectiveness for some measures varies widely and may not be cost effective in some circumstances.

1.11 These 22 measures, however, can achieve significant CO_2 reduction in 2020 and 2030 for existing ships and new ships. Detailed cost-effectiveness analyses for new ships and for new and existing ships together, and marginal abatement cost curves by ship types are shown in Chapter 6.

Possible uses of these analyses and this report

1.12 The outcome of this report does not favour a particular market-based approach, or specific energy efficiency standards. The methodologies and analysis are structured to support the development and implementation of any regulatory and/or corporate policies that may be adopted. As well we expect that the results may be used by ship designers, builders, owners and operators as a tool in their decision making to employ one or more technologies or operational measures. The methodology and inputs are structured such that each can be varied should new information be incorporated or to posit and test different views on any of our assumptions.

1.13 The approach allows policy makers and others to factor new or different information about measures and/or basic assumptions easily. As the report provides and documents the assumptions and input data, as well as an easy to follow and replicate approach, expanded or revised analysis can be accomplished quickly in a standardized manner. In turn, these

[1] This estimate excludes all non-speed reduction operational measures and assumes that the speed-reduction operational measures identified in this report are a proxy for design speed reductions all else being constant. Other operational measures account for about 2-3% of potential emissions reduction at net MAC of less than or equal to zero (i.e., cost savings).

can provide customized cost-effectiveness estimates for a suite of selected measures and specific ship type, size, and age, and in turn may be used to derive customized MACC.

1.14 The cost-effectiveness of measures and MACCs presented in this report can be used for a number of purposes.

.1 Improve the projections of future emissions. Emission projections can be based on projections of increased demand and energy-efficiency improvement estimates. In many studies, efficiency improvement estimates are based on historical data or on expert judgement. By using a MACC to estimate energy-efficiency improvements, more accurate projections can be made, incorporating fuel price projections and other variables. In turn, our methodology can easily provide estimated gross CO_2 reductions by ship type, size, and age or any combination or aggregation thereof, for any policy assessment scenario under consideration.

.2 Improve policy design choices. Some policies may incentivize one set of measures, while other policies may take another set into account. Some policies may affect some ship owners and operators more than others or some ship types more than others. The cost-effectiveness of measures and MACC presented in this report allow policy makers to make an informed choice about which measures to include in the governmental and company policy options. They also allow them to identify which segments of the shipping industry or an owner's fleet are affected by the policies as well as the extent.

.3 Assist in the assessment of policies. MACC and corresponding estimates of the CO_2 emission reduction potential may be used to analyse the costs, effects and cost-effectiveness of policy instruments. They can be used to assess the costs imposed on the shipping sector by efficiency standards, the in-sector abatement incentivized by fuel levies or cap-and-trade schemes, and the costs and effects of baseline-and-credit trading schemes. The marginal abatement cost curves in particular can be used to:

.1 Support cost/benefit analysis for future regulation of the international maritime industry.

.2 Understand how the different parts of the industry will be affected by mandated and increasing energy-efficiency/CO_2 emissions reduction requirements.

.3 Understand how a vessel owner or operator decides which energy efficiency measures to do first, and when to employ a measure (e.g., opportunity costs, barriers, importer/shipper expectations).

.4 Contribute to cost-benefit analyses of climate policies for shipping. By clarifying the relation between costs and effects, MACC are a crucial element of any cost-benefit analysis of policies. And to;

.5 Assist ship owners and operators in the selection of abatement measures. An overview of the cost-effectiveness of the different measures and combinations of abatement measures will help ship owners and operators select the measures that may be of interest to them, thus limiting the search costs and increasing the efficiency of shipping.

CHAPTER 2

INTRODUCTION

2.1 Shipping accounts for approximately 3% of manmade green-house gas (GHG) emissions and, therefore is considered to have a significant contribution to climate change past years, a number of proposals have been put forward to limit or reduce the climate impact of shipping. In order to evaluate these proposals adequately, it is essential to have good data about the costs of abatement and the abatement potential, preferably in a flexible way so that ad-hoc analysis can be made per ship type, for different ship sizes, and age.

2.2 In recent years, a number of reports have been written on measures that reduce CO_2 emissions and/or improve fuel efficiency of shipping and their cost-effectiveness (AEA, 2008; Buhaug et al 2009; CE Delft, 2009; Crist 2009; Eide et al, 2009)[2]. Most of these studies rely heavily on manufacturers' data for some measures and some lack transparency. While building on the other studies, this report aims to improve the transparency and the accuracy of the estimates. We included additional measures and validated costs and abatement estimates with naval architects, marine engineers, and service providers and with users of the technologies to the extent possible.

Brief overview of the methodology

2.3 This report follows a six-step approach.

.1 Identification of CO_2 abatement technology.
.2 Calculation of the cost-effectiveness of individual measures
.3 Evaluation of the sensitivity to input parameters
.4 Identification of constraints and barriers to implementation
.5 Rank ordering technologies
.6 Calculation of MACC as a function of ship type

2.4 First, the energy saving technology and operational measures were identified and defined. We then developed the assumptions and key parameters for each measure as well as for the maritime shipping sector. Next we refined our basic equations and calculate the cost-effectiveness of each energy-efficiency improvement for each measure as a function of vessel type, size and age. The cost-effectiveness was expressed as the costs per unit of CO_2 emissions abated. Then we examined the sensitivity and corresponding changes in estimated cost-effectiveness in response to the fluctuations of discount rates and fuel prices. Then market barriers and other constraints on a vessel owner or operator's willingness to implement a measure or group of measures were identified. Fifth, an approach to rank order the measures or group of measures based on their cost-effectiveness and the appropriateness of the measure was developed; including impact on percent (%) reduction, ease of implementation, and other factors. The individual cost-effectiveness was combined to develop marginal abatement cost curves (MACC). The MACC shows plotted abatement costs against CO_2 emissions reductions for the world fleet or a segment thereof. We present the MACC with high and low estimates, with and without speed reductions (as speed reductions are often the measure with the highest abatement potential) and performed a sensitivity analysis with regard to fuel price and discount rate.

2.5 The approach required identifying all cost and benefit items related to the applications of fuel-efficiency improvement measures. The costs include the capital costs, costs due to loss of service and time, and operational costs. Cost savings were measured in

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2 In the following, we will use energy-efficiency improvement and CO2 abatement as synonyms.

reduced carbon-based fuel consumption. This approach required a substantial data input. We acknowledge receiving useful data from our authors and through cooperation within the Society of Naval Architect and Marine Engineers (SNAME). Some data required making assumptions and other qualifying limitations. A prime example was future fuel price. The methodologies included several detailed analysis that derive, delineate and address all assumptions and their respective impacts on cost effectiveness. These assumptions included the fuel price, the discount rate, the suitable ship types and sizes for different fuel-saving measures, freight rates, opportunity costs, and the learning rate for the introduction of new measures as this relates to capital and service or operational costs. It should be noted that data for this study on the abatement measures was obtained from published sources including both manufacturers and other studies. We attempted to corroborate this data with direct interviews of operators and others with experience with the measures. However, further work needs to be done on the actual in-service cost, reliability, variability, and effectiveness of these measures. SNAME's Technical & Research Committee will continue to evaluate these measures.

2.6 Two factors were singled out for sensitivity analyses because their changes may significantly impact the cost effectiveness. These were future fuel prices and the interest or discount rate. The write-down of the costs of a technology measure, and technological progress reducing the costs of a technology over time are related to a ship's remaining life and are incorporated into our analysis of cost effectiveness.

Background

2.7 Ship-based CO_2 emissions have been an increasing concern for years. They accounted for 3.3% of total worldwide CO_2 emissions in 2007 (Buhaug *et al*, 2009) or more than 12% of CO_2 emissions from the transportation sector in 2005 (Wang, 2010). International shipping, which represents ships transiting between ports from different countries, accounts for approximately 2.7% of total CO_2 emissions in 2007 *(*Buhaug *et al, 2009)*. Recent studies have documented the steady increase of ship-based CO_2 emissions, along with other types of emissions (Corbett *et al*, 1997; Endresen *et al*, 2003; Wang *et al*, 2009) The expansion of international trade arising from globalization has led to substantial increases in CO_2 emissions from ocean shipping (Eyring *et al*, 2005; Chiff *et al*, 2009). CO_2 emissions from the international maritime industry doubled between 1994 and 2007. Without policy measures, CO_2 emissions are projected to grow between 150% and 300% by 2050 despite significant market-driven efficiency improvements (Buhaug *et al*, 2009).

2.8 Several policy options for increasing energy efficiency are being considered by the International Maritime Organization (IMO). As policy makers and stakeholders are evaluating the policy options and their impacts, it would be useful to have reliable data on the cost-effectiveness of technical and operational measures. It is one of the objectives of this study to provide these data, both for individual measures and in an aggregated manner as a marginal abatement cost curve.

Review of Literature, Reports and Studies

2.9 One of the most studied operational fuel efficiency improvement measure is speed reduction. Notteboom *et al* (2008) calculate the relationship between fuel consumption and speed and explain the economic saving and environmental benefit from slow steaming (Notteboom *et al*, 2008). Corbett *et al* (2009) consider the opportunity cost and calculate the cost effectiveness of slow steaming containerships (Corbett *et al*, 2009). They divide the speed reduction into two scenarios. One scenario assumed no additional ships being added to cover the lost service when ships reduce speed; the other scenario was the addition of ship(s) to ensure the same level of service. They found that the cost effectiveness in the second scenario, which is closer to real shipping operations, was prohibitively high. CE Delft *et al* (2010) considered the oversupply of fleets, which creates a unique opportunity to reduce speed and CO_2 emissions in a cost effective manner. They estimated a maximum of 30% emissions from bulkers, tankers, and container vessels can be reduced using the current oversupply (CE Delft *et al*, 2010).

2.10 Subsequent studies have started to evaluate the cost effectiveness and applicability in more detail, while often also adding measures. The IMO 2009 GHG Study grouped measures to show which measures are mutually exclusive and which measures can be implemented simultaneously (Buhaug *et al*, 2009). That report illustrated that for some technologies, the abatement costs were negative, meaning those measures could save money for the industry due to net fuel efficiency improvements with a net reduction in overall costs due to carbon-fuel savings. The most comprehensive overview to date is CE Delft *et al* (2009) which presented a cost-effectiveness analysis and a marginal abatement cost curve for 29 measures in 12 groups, taking into account 14 different ship types, often subdivided in several size categories (CE Delft *et al*, 2009).

2.11 There is a growing body of literature on the costs and benefits of individual measures. For example, Propulsion Dynamics estimates the cost and potential savings of hull and propeller performance monitoring (Munk *et al*, 2006); Man Diesel analyzes the costs and savings from engine de-rating (Jespersen *et al*, 2009) and turbo-charger cut-off (MAN Diesel, 2009) and Wettstein *et al* from Wärtsilä computed the payback time of engine de-rating as well (Wettstein *et al*, 2008). There are papers focusing on a bundle of fuel-efficiency improvement measures as well. Green Ship of the Future studied a bundle of technologies including waste heat recovery, turbo charging and variable nozzle ring, and pump and auxiliary system and calculated the capital costs with fuel savings (Odense Steel Shipyard Ltd *et al*, 2009)

Our Approach

2.12 This report builds on previous reports. It improves the analysis in the following ways:

.1 We included additional measures, and incorporated incorrectly categorized measures as supporting means of measures (e.g., hull monitoring supports hull cleaning and propeller polishing).

.2 We reviewed and updated data on costs and abatement potential and the applicability to both new and existing ships of individual measures and cross-checked it with ship owners and operators, naval architects and marine engineers.

.3 We revisited and updated key assumptions (e.g., fuel price and discount rates).

.4 We explicitly described assumptions and methodology in order to present a more transparent analysis.

.5 We estimated the cost effectiveness of measures for both new and existing ships as a function of ship size and for existing ships by age.

.6 We developed marginal abatement cost curves as a function of ship type for new and existing ships and examined the role of measures such as speed reductions on MACC estimates.

2.13 All assumptions and our methodology are explicitly described with supporting analysis. Chapter 3, *Methodologies / Approach, and Assumptions* is devoted to elaborating the assumptions we made throughout the report, the limitations of this report, and how to address these limitations. We expect that by making assumptions and limitations clear, policy makers can be better informed and the industry will be enabled to identify the aspects of the analysis to be improved. We explicitly accounted for uncertainties in costs and abatement estimates. These stem from different operational profiles of ships, price differences between equipment manufacturers, ranges in estimates for efficiency improvements and other factors. We think it is essential to take these uncertainties into account when evaluating policy proposals.

2.14 Chapter 4 identifies *Barriers to Improving Shipboard Energy Efficiency*. We discuss how market mechanisms and current relationships among ship owners, operators, charters, and cargo owners lead to the market inefficiency and reluctance for market participants to use fuel-saving technologies and operational options, and how such inefficiencies affect owner or operator decisions on implementation (e.g., often through simple cost-benefit analysis or payback periods). We also consider how these barriers could and are being removed by better corporate and regulatory policy design.

2.15 This study draws from a wider set of data. CE Delft (2009) is our primary source, supplemented with interviews by Navigistics Consulting and others. We collaboratively reviewed and refined much of this data (CE Delft, 2009). We also gathered additional data through the cooperation of experts within SNAME and through conducting an online data survey. Detailed descriptions of abatement measures, including all assumptions, cost effectiveness data, applicability (i.e., ship types and sizes, new ships and existing ships), and other factors are described in Chapter 5, Description of Abatement Measures. Table 2-1 are the abatement measures we studied. Table 2-2 are the vessel types we examined.

Table 2-1: Abatement Measures and Groups of Related Measures

Operational Speed Reduction (10%)
Operational Speed Reduction (20%)
Weather Routing
Autopilot upgrade/adjustment
Propeller polishing at regular intervals
Propeller polishing when required (include monitoring)
Hull cleaning
Hull coating 1
Hull coating 2
Air lubrication
Propeller rudder upgrade
Propeller boss cap fin
Propeller upgrade
Common Rail
Main Engine Tuning
Waste Heat Recovery
Wind engine
Wind kite
Solar Power
Speed control pumps and fans
Energy saving lighting
Optimization water flow

Table 2-2: Vessel types

Crude Tanker
Product Tanker
Chemical Tanker
LPG Tanker
LNG Tanker
Other Tankers
Bulker
General Cargo
Other Dry General Cargo
Container Unitized
Vehicle Carrier Unitized
RoRo Unitized
Ferry: Passenger
Cruise ship

2.16 Chapter 6, Analysis and Estimation of CO_2 Marginal Abatement Cost Curves, presents our findings. The cost-effectiveness of different measures for 318 categories of ships identified by specific type, size and age are presented. Appendix III contains our estimates of cost-effectiveness for each ship type by size and age. Uncertainty in the cost effectiveness (high and low estimates) and sensitivity to external variables such as fuel price and discount rate provide a range for each. In Appendix IV, we present MACC without speed reductions (as speed reductions are often the measure with the highest abatement potential) for fourteen ship types for the year 2020[3]. A partial set of set of aggregated MACC is available at http://www.sname.org/SNAME/climatechange/MACreport and http://www.theicct.org/programs/Marine. The specific measures which make up each MACC estimate are transparent.

3 We aggregated the MACC by ship type as we could potentially generate three hundred sets of six curves, or 1908 curves.

CHAPTER 3

METHODOLOGY/APPROACH AND ASSUMPTIONS

3.1 This chapter first describes the methodology and data for calculating the cost-effectiveness of individual measures and the marginal abatement cost curve (MACC) for the world fleet and various segments thereof. Next, this chapter introduces the data sources and the online survey we made available for industry experts to collect related cost and fuel-efficiency improvement data as well as the methodology we use to forecast future fuel prices. The variables and data are dependent on a variety of assumptions. These assumptions include: the costs of fuel; the appropriate discount rate to use in determining the marginal abatement cost; the opportunity costs of vessel capacity / time; change in service costs; the age of the fleet (to assess retrofitting measures); and the technology learning curve.

Methodology

3.2 The methodology comprises six steps. Each of these steps is described below.

.1 Identification of CO_2 abatement technology.

.2 Calculation of the cost-effectiveness of individual measures

.3 Evaluation of the sensitivity to input parameters

.4 Identification of constraints and barriers to implementation

.5 Rank ordering technologies

.6 Calculation of MACC as a function of ship type

3.3 The first step identified CO_2 abatement technologies and operational measures. This was done through a comprehensive literature survey, a web-based survey and contacts with experts and technology users. The identification included collecting data on costs and abatement potential. More details on data sources can be found in Chapter 5.

3.4 The second step was the calculation of the cost-effectiveness of individual measures. Cost-effectiveness is by definition the quotient of costs and effect. This is also referred to as marginal abatement costs (MAC). CO_2 abatement technology often requires an investment in new technology. Generally, the technology requires maintenance and other operational costs. We call these service or operating costs. Since installing the technology may take time and/or cargo space, there may be opportunity costs involved (the time and space could have been used to generate revenue) due to loss of service. In addition, there are fuel savings which are a negative cost or a benefit. We annuitized all costs; the cost-effectiveness is the total annual costs divided by the CO_2 abated per year. The discount rate used to annuitize capital costs reflects the cost of capital of the maritime industry. The use of annual costs (see Chapter 6), yields equivalent results to calculating the net present value of future costs and benefits.

3.5 Based on the description above, we model the cost function of installing new technologies in Equation (1).

$$\boxed{\Delta C_j = K_j + S_j - E_j + \sum O_j} \tag{1}$$

Where:

ΔC_j is the change of annual cost of the technology j;
K_j is the capital cost of the technology j, discounted by the interest rate and written down over the service years of the technology or the remaining lifetime of the ship, whichever is shortest;
S_j is the service or operating costs related to use the technology.
$\sum O_j$ is the opportunity cost related to lost service time and/or space due to the installation of the technology; and
E_j is the fuel expenditure savings from that technology, which is a product of the price of fuel and the saving of fuel as described in Equation (2).

$$\boxed{E_j = \alpha_j \times F \times P} \qquad (2)$$

Where:

α_j is the fuel reduction rate of technology j;
F is the pre-installation or original fuel consumption for a ship,
P is the fuel price.

The original fuel consumption of a ship of a certain type, size and age is taken from the IMO 2009 GHG study. It is assumed to be constant over time so therefore the baseline does not need to make assumptions about which technologies would be used to achieve business-as-usual (BAU) energy-efficiency improvements.

3.6 The cost-effectiveness of a given technology is therefore determined in Equation (3) by:

$$\boxed{MAC = \frac{\Delta C_j}{\alpha_j \times CF \times F} = \frac{K_j + S_j - E_j + \sum O_j}{\alpha_j \times CF \times F}} \qquad (3)$$

CF is the carbon emission factor, i.e. the mass of CO_2 emitted when a unit of mass of fuel is burned.

3.7 Equation 3 can be adapted to the cost-effectiveness for operational measures as well. The difference is that some operational measures may not require capital cost. Rather, these require operating capital to cover direct service cost (e.g., hull cleaning). For some operational measures, capital input is needed such as extra ships (e.g., slow steaming) as well as a voyage management or monitoring system.

3.8 This report presents a cost-effectiveness analysis of measures to increase the fuel-efficiency of ships. Such an analysis can be instrumental to evaluations of the social costs and benefits of policy instruments, scenario development and other related aims. It should, however, not be mistaken for the investment appraisal by private operators. Although cost-effectiveness analysis and investment appraisal have commonalities, including assumptions on interest rates, write-down period, et cetera, they may yield different results depending on the appraisal method employed. This section discusses the relations between the analysis presented here and three methods for investment appraisal, viz. the net present value, the internal rate of return and the payback period.

3.9 The aim of investment appraisal is to decide whether from the perspective of a firm, a project is worth investing in or not. There are several ways to evaluate projects financially.

3.10 The simplest method to evaluate investments is by estimating the payback period. The payback period is simply the investment divided by the net savings (or cash flow) per period. For example, an investment of USD $1000 that saves USD $400 annually has a payback period of 2.5 years. While the payback period is often used as a rule-of-thumb evaluation of investments, it has several disadvantages. First, it does not properly account for the time value of money as it has no discount rate. Second, it gives no information on the total profits over the life of the investment. Third, it cannot be universally applied as it may not yield unique values for investments with variable cash flows.

3.11 A more sophisticated way to evaluate investments is the net present value (NPV). It is an indicator of the value of an investment. By definition, this is the difference between the capital costs of an investment and the present value of the future flow of profits. The formula for NPV is:

$$\boxed{NPV = R_0 + \sum_{t=1}^{T} \frac{R_t}{(1+i)^t}} \qquad (4)$$

Where:

R_o – the investment at t=0
T – the lifetime of the investment
R_t – the net cash flow (cash inflows minus expenditures) at time t
i – the discount rate

When calculating the NPV, assumptions must be made on the lifetime of the investment and the discount rate must be determined. The discount rate can be based on a firm's weighted average cost of capital (WACC), adjusted in order to account for differences in risk; or considered to be the sum of the risk-free discount rate plus a risk premium.

3.12 Another way to evaluate investments is to calculate the internal rate of return (IRR). It is an indicator of the yield of an investment, not of its value. By definition, the internal rate of return is the discount rate for which the NPV is zero. In other words, it is the discount rate for which an investment breaks even. The IRR has some disadvantages compared to the NPV. First, it gives no information on the total profits over the life of the investment. Second, it has no unique solution when the cash flow is negative in a future year. When calculating the IRR, assumptions have to be made on the lifetime of the project, but not on the discount rate, as this is the outcome of the analysis rather than the input.

3.13 In comparing the three ways to evaluate investments, payback time is the simplest. One does not need to evaluate the lifetime of the investment and the implicit assumption on the discount rate is that it is zero. In other words, capital is costless. Assessing an IRR requires of capital, preferably adjusted for the risk of the investment. NPV is the most accurate approach to evaluate investments as it gives information on the total expected profits, and requires the cost of capital as an input in addition to the assumption on the lifetime of the investment. Using the NPV to evaluate investments gives information on the total expected profits, but requires the cost of capital as an input in addition to the assumption on the lifetime of the investment. Table 3-1 shows the advantages and disadvantages of the three methods.

Table 3-1: Pros and cons of investment appraisal methods

Appraisal method	Main advantage	Main disadvantages	Input
Payback period	Easy to use	Does not account for capital costs Does not convey information on yield or profit Not universally applicable	Capital expenditures Operational expenditures Fuel savings Fuel price
Internal Rate of Return (IRR)	Gives information on yield of an investment	Does not convey information on profit Not universally applicable	All of the above Lifetime of the investment
Net Present Value (NPV)	Gives information on total profit of an investment		All of the above Discount rate

3.14 An example can illustrate the differences between the three methods. Consider an investment with a payback time of five years and a constant cash flow (e.g. investment of 100 in year 1 and returns of 20 in each year including the first). If this investment has a lifetime of five years, it has an IRR of 0%. If the firm evaluating the investment uses a discount rate of 15% for these types of investment, the NPV equals minus 20% of the investment. Hence, it is not profitable. If, however, the investment has a lifetime of ten years, not five, the IRR rises to 20% and the NPV at a discount rate of 15% increases to plus 13% of the value of the investment. Hence, even though the payback time is the same, the longer lifetime of the investment turns it into a profitable one. Since IRR is an indicator of the yield of an investment and NPV of its value, rank ordering projects on the basis of their IRR may show different results than rank ordering them on the basis of their NPV. A rank order on the basis of payback times may yield yet other results.

3.15 Another concept provides yields the same numerical calculation as the NPV is the cost-effectiveness analysis. Cost-effectiveness analysis does not identify high yields or value of investments, but it identifies the costs associated with achieving a certain goal. The annual costs are defined as the sum of the annualised capital costs, the annual operational costs, and the annual savings in fuel costs. Since the emission reduction is related to the fuel savings, one can write the following equation for cost effectiveness:

$$\boxed{C.E. = \frac{CapEx + OpEx + OC - FuelSav}{FuelSav \times \left(EF / p_{Fuel}\right)} = c \times \left(\frac{CapEx + OpEx + OC}{FuelSav} - 1\right)} \quad (5)$$

Where:

C.E. – cost-effectiveness
CapEx – the annuitized costs of capital
OpEx – the annual operational expenditures
OC – Opportunity costs related to lost service time
FuelSav – the annual value of fuel expenditure savings
EF – the emission factor of the fuel
p_{Fuel} – the price of fuel
c – a constant being the price of fuel divided by the emission factor

In order to calculate annuitized capital costs, one needs to make assumptions about the lifetime of an investment and the discount rate. These are the same assumptions as need to be made for the calculation of the NPV of an investment. Using annuitized capital costs reflects a situation where a company takes out a loan to fund an investment and the loan has to be repaid over the lifetime of the investment. The cost-effectiveness according to this calculation yields the same results as the cost-effectiveness with NPV and discounted future emissions. Hence, if measures are rank-ordered on cost-effectiveness, they show the same order as when they are rank-ordered on NPV. Rank ordering the same measures on IRR or payback time yields different results, however. Our analyses are based on an assumed zero marginal income tax rate, similar to certain tonnage tax systems in use around the world.

3.16 The third step was the evaluation of the sensitivity to input parameters. We performed a sensitivity analysis for fuel prices and discount rates. For more details on the assumptions, see Chapter 6.

3.17 The fourth step was the identification of constraints and barriers to implementation. We identified technical barriers for each individual measures based on information from manufacturers, users of the technology, and other experts. In addition, several general barriers and constraints were identified. These are described in Chapter 4.

3.18 The fifth step was to rank order technologies based on their cost-effectiveness. The rank-ordering was done separately for each of the 318 different combinations of ship type, size, and age that were considered in our model. Of course, for each combinations of ship type, size, and age only those technologies were rank ordered that can be implemented on those ships.

3.19 The sixth step was to develop Marginal Abatement Cost Curves (MACC). MACC are plots of the cost effectiveness of additional measures against the resulting cumulative reduction in CO_2 emissions. For each combinations of ship type, size, and age, there are a suite of technical and operational measures that can be applied in order to reduce fuel consumption and emissions. Not all technologies and operational measures can be applied together. In other words, the cost and effectiveness are not a simple summation. Moreover, if different measures are implemented on the same ship, the cost-effectiveness of the measures changes because the effect of each additional measure is reduced by the fuel savings realised by previous measures. Our construction of a MACC assumed that the most cost effective option (which is the option with the highest net present value) would be implemented first, the next most cost effective option second, and so on.

3.20 Our MACC were based on demand forecasts from the IMO 2009 GHG Study and used a frozen technology baseline. In other words, the IMO report constructed a hypothetical baseline where the number of ships and their fuel use grows in line with growing demand. In this hypothetical baseline, ships built in 2020 and 2030 would have the same fuel-efficiency as the average of that category of ships had in 2007. The advantage of this method is that it shows which energy-efficiency improvements are possible and that it does not depend on arbitrary judgement of which technologies or operational measures would be implemented in a BAU scenario and which would not be employed.

3.21 When evaluating the MACC, it is important to realize the implications of the baseline choice. For example, in this study, typically, the MACC showed a large CO_2 abatement potential with a net cost-effectiveness less than zero, i.e. a potential that can be achieved at a profit. In a perfect market, all these measures would be implemented without any policy intervention, because they were profitable. In reality, there may be barriers and constraints that prevent the implementation of some of these measures, though it is expected that most cost-measures would be implemented (see Chapter 4).

Data for cost and savings of technologies and operational measures

3.22 Our data were collected mainly from four sources:

.1 A literature review. Wartsilä (2008) was a starting point, Buhaug *et al* (2009) and CE Delft *et al* (2009) provided the cost and fuel-efficiency improvement data for most technologies and operational options. We apply these data using our methodology.

.2 Second, we used some publicly available studies of specific technologies published by various companies such as Green Ship Inc., Wärtsilä, and B&W.

.3 Third, we consulted with experts within the Society of Naval Architect and Marine Engineers (SNAME), and industry sources who provided data and their insights. We then contacted and interviewed or consulted experts for their advice on data and shipping practices. Some of these experts were acknowledged in the end of this report, while some were anonymous per their request.

.4 Fourth, we conducted an online survey. In the survey, we asked questions about the capital cost of employing using a technology, the lost service from applying technologies or operational measures, the fuel savings, applicable ship types, and their estimates on future energy-efficiency improvement and cost reduction.

Assumptions

3.23 Besides the data input, the calculation of the cost effectiveness depends on a host of assumptions and estimations. They include the fuel price, discount rate, learning curve, and ship age distribution. This section briefly introduces these factors.

Fuels

3.24 The fuel price between 2007 and 2030 is one of the key elements in the cost-effectiveness calculations. We projected the fuel price through 2030. The projection was based on:

.1 The crude oil price projections from the Energy Information Agency (EIA).

.2 The correlation of historical heavy fuel oil (HFO) prices and crude oil prices.

.3 The projected impact of the MARPOL Annex VI regulation on the maritime fuel prices.

The details for fuel price projection are listed in the Appendix A.

3.25 The U.S. Energy Information Agency (EIA) publishes crude oil price projections in the Annual Energy Outlook (AEO). The projection as published in the Annual Energy Outlook 2009 is used to estimate the 2030 bunker fuel price. In the AEO2009 reference case, world oil prices rise to $130 per barrel (real 2007 US dollars) in 2030; however, there is significant uncertainty in the projection, and 2030 oil prices range from $50 to $200 per barrel in alternative oil price cases. The low price case represents an environment in which many of the major oil-producing countries expand output more rapidly than in the reference case, increasing their share of world production beyond current levels. In contrast, the high price case represents an environment where the opposite would occur: major oil-producing countries choose to maintain tight control over access to their resources and develop them more slowly.

3.26 Heavy fuel oil (HFO) is primarily the residue of the distillation process of crude oil. HFO is the fuel grade that is used the most by the world shipping fleet. When looking at historical prices for HFO and crude oil, a well-defined relationship can be established. Using EIA data on prices of HFO in Singapore and West Texas Intermediate (WTI) crude oil prices, we found that the price of HFO in USD per metric tonne is on average five (5) times the price of WTI in USD per barrel. Figure 3-1 shows the correlation of both prices in the period 2000-2010. An analysis of the prices for a different time periods, for example using Brent instead of WTI as the benchmark for the crude oil price; or using Rotterdam LSO instead of Singapore HFO, did not significantly alter this result.

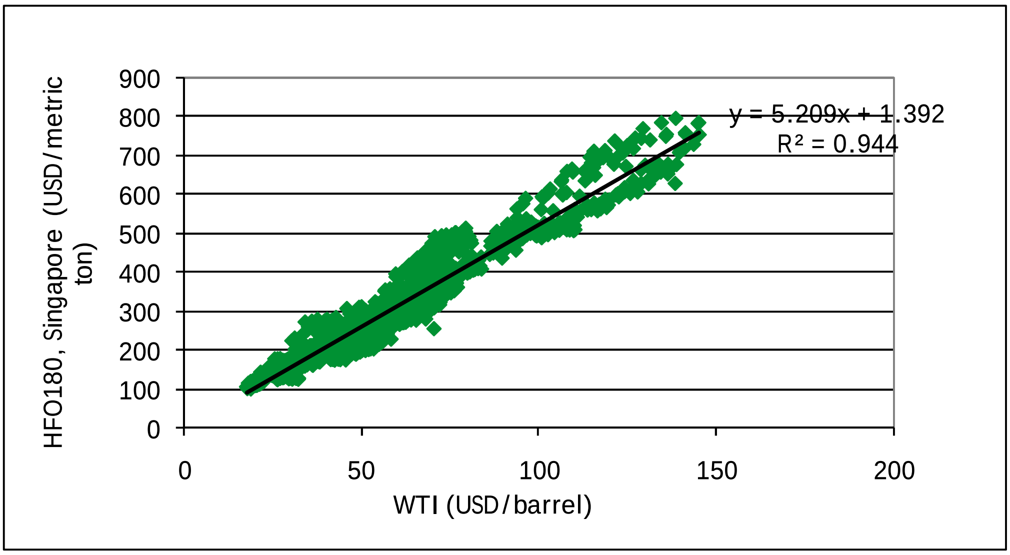

Figure 3-1: Historic relationship between crude oil price ($/barrel) and HFO 180 spot price (Singapore, $/mt), 2000-2010

3.27 Future requirements on the sulphur content of maritime fuels are likely to affect prices. The sulphur content is regulated by Annex VI of the MARPOL convention. In October 2008, the IMO's Marine Environmental Protection Committee (MEPC) adopted a revision of this Annex which, among other things, sets stricter standards for the sulphur content of maritime fuels. The maximum sulphur content limit will decrease from 4.5% m/m today to 3.5% m/m in 2012 and on to 0.5% m/m in 2020 or 2024 (depending on the availability of low sulphur fuels as determined in 2018) and to 0.1% m/m in emission control areas (ECAs) (see Table 3-2).

Table3-2: MARPOL Annex VI Fuel Sulphur Limits

<table>
<tr><td rowspan="2">Date</td><td colspan="2">Sulphur Limit in Fuel (% m/m)</td></tr>
<tr><td>ECA</td><td>Global</td></tr>
<tr><td>2000</td><td>1.5%</td><td rowspan="2">4.5%</td></tr>
<tr><td>2010.07</td><td rowspan="2">1.0%</td></tr>
<tr><td>2012</td><td rowspan="2">3.5%</td></tr>
<tr><td>2015</td><td rowspan="2">0.1%</td></tr>
<tr><td>2020*</td><td>0.5%</td></tr>
<tr><td colspan="3">* - alternative date is 2025, to be decided by a review in 2018</td></tr>
</table>

3.28 Recently, a number of studies on the costs of low sulphur fuels have been published. An IMO expert group estimated in 2007 that low sulphur fuels have a historical price premium of 50% to 72% (BLG 12/6/1). For 2020, the expert group report of model runs, suggesting a price increase of 25%. Since then, additional studies have been published. In the Purvin *et al* (2009) study, it is estimated that bunker fuel with 0.5% maximum sulphur content will cost $ 120 to $ 170 more per tonne than the current high sulphur quality, leading to an increase of the costs of bunker fuel in the range of 30-50%, depending on the process option (Purvin *et al*, 2009). In a study of the Ministry of Transport and Communications Finland (2009), it is estimated that HFO with a maximum sulphur content of 0.5% will be about 13-29% more expensive than the HFO with a maximum sulphur content of 1.5%. Based on these findings, we assumed a cost increase range of 10-50%, with a middle estimate of 30% (Ministry of Transport and Communications, 2009).

3.29 We did not examine the potential for switching from HFO to distillates (MDO/MGO) in order to meet the lower sulphur requirements before our 2030 case. Nor did we explicitly examine fuel costs as it may relate to increased refining capacity of low sulphur fuels as demand rises and oil companies respond to the market. These would have the likely impact of significantly increasing the cost of marine fuels from 2020 (or 2024) onwards which would significantly reduce the marginal abatement cost of fuel saving technologies in our 2020 scenarios.

3.30 Applying the regression line as depicted in Figure 3-3, the HFO prices that correspond to the EIA crude oil price projections are about $260, $680, and $1045 per metric ton. Assuming that the transition to distillate fuels is completed by 2030 and that the low sulphur fuel costs about 30% more than HFO, the bunker fuel price was projected to be approximately $745 per metric ton in the low price case, about $880 per metric ton in the reference case, and $1020 per metric ton in the high price case. These projections are in 2007 dollars. To facilitate the analysis of this report, estimates in Table 3-3 are used for fuel prices in 2020 and 2030. For this report we used fuel prices in Table 3-4.

Table 3-3: Fuel price projection

EIA fuel price projections (2030, USD per barrel crude)	Corresponding HFO price (USD per metric tonne)	HFO price increase due to low sulphur fuel requirements	Resulting 2030 fuel price (USD per metric ton)
		10%	290
50	260	30%	745
		50%	1150
		10%	340
130	680	30%	880
		50%	1355
		10%	395
200	1045	30%	1020
		50%	1565

Table 3-4: Fuel price used in this report

	Fuel Price Projection ($ per metric ton)	
	Fuel Price in 2020	Fuel Price in 2030
Low estimate	500	700
Central estimate	700	900
High estimate	900	1100

The Appropriate Discount Rate to Use in Estimate Marginal Abatement Cost

3.31 A discount rate is used when a capital cost (i.e., a fixed initial investment) is required for the CO_2 abatement technology. The discount rate is used in spreading the capital costs over the expected life of the technology. Alternatively, the discount rate can be used for determining the present value of future benefits or costs. The discount rate can have a large impact on the results. The higher the discount rate used (all else equal), the lower the present value of future costs/benefits. Accordingly, selection of the proper discount rate is important for accurately determining the Marginal Abatement Cost. The discount rate is not a simple concept to understand nor is it easy to precisely calculate.

3.32 The discount rate (also referred to as the cost of capital, opportunity cost, or weighted average cost of capital) should reflect the level of risk inherent in the cash flows being considered. Discount rates, therefore, vary according to the risk (uncertainty) of the expected cash flows. A risk free series of cash flows would be discounted at the lowest discount rate. US Treasury securities are currently used as the proxy for a risk free discount rate. The interest rates on U.S. Treasury securities, however, vary with the length of time to maturity. The change in interest rates v. time to maturity is called the yield curve. The yield curve for U.S. Government securities (interest rates) is shown over a wide range of maturities in Table 3-5.

Table 3-5: US Treasury Yield Curve 5/7/2010Source: US Federal Reserve Board

Months	Rate
1	0.11%
3	0.14%
6	0.22%
12	0.39%
24	0.88%
36	1.41%
60	2.29%
84	2.99%
120	3.56%
240	4.20%
360	4.36%

3.33 The typical time frame for considering capital expenditures on existing vessels is on the order of five to ten years. This provides an average U.S. Treasury rate of approximately 3 percent.

3.34 Securitization transactions (where cash flows, e.g., charter payments are guaranteed by a low risk large integrated oil company) in the maritime industry have been done at rates of approximately 100 to 150 basis points above the underlying guarantors borrowing rate. This would indicate that a minimum "risk free" discount rate to use in a marginal abatement cost analysis would be on the order of 4.0 to 4.5 percent.

3.35 However, the benefits and/or costs of CO_2 reduction are not necessarily "risk free." Therefore, a higher discount rate should be used to reflect the greater uncertainty in the expected benefits and/or costs. The typical approach to determining the appropriate discount rate to use in discounting future cash flows to the present is the weighted average cost of capital (WACC) for companies operating in the industry. Expected returns on investments by equity investors is only one of the inputs required to determine the appropriate discount rate. As virtually all investments in ships use some form of financing, the cost of that financing (i.e., debt) must also be included. The formula for determining the WACC is shown in Equation 5:

$$\boxed{\text{WACC} = (\%\text{Equity} \times \text{ROE}) + (\%\ \text{Debt} \times \text{Int. Rate} \times [1 - \text{TR}])} \qquad (5)$$

Where:

% Equity = Percentage of a firm's capitalization comprising equity
ROE = Expected Return on Equity (Cost of Equity)
% Debt = Percentage of a firm's capitalization comprising debt also equal to (1- %Equity)
Int. Rate = Interest rate on the firm's debt
TR = Tax Rate this can range from near zero in some countries for shipping to the US's 35% marginal corporate tax rate.

3.36 The approach used to determining the appropriate discount rate to use in analyzing the Marginal Abatement Costis based on the following three analytical steps:

.1 Determining the weighted average cost of capital for the deep sea foreign transportation of freight industry (SIC Code 441).

.2 Calculating the weighted average cost of capital for publicly traded companies prominent in the international ocean freight industry.

.3 Using the results of steps 1 and 2 to arrive at a reasonable discount rate.

3.37 Obviously, the closer the approach reflects the risks of expected benefits/cost of the abatement technology, the more accurate the discount rate will be for determining the marginal abatement cost.

3.38 To validate our discount rate estimates, we then considered the weighted average cost of capital for publicly traded shipping companies. To test the validity of the 9.5 percent discount rate derived in the first step, we estimated WACC for three publicly traded (New York Stock Exchange) shipping companies, identified as Company A, Company B, and Company C (a mix of tanker and bulk carrier owner/operators). The WACC was estimated for each of the three in a four step process:

.1 The capital asset pricing model (CAPM) is used to estimate the Expected Return on Equity (Cost of Equity or ROE). The CAPM formula is shown below.

.2 ROE = Riskless Rate + Beta * (Equity Premium Rate). Equity Premium Rate = Expected Total Market Return - Riskless Rateplus the previously cited industry risk premium and a size premium based on each company.

.3 Estimate the borrowing cost (interest rate) for each of the companies (constant maturities).

.4 Determine the Capital Structure (percentage debt and equity) for each company.

.5 Calculate the WACC using the WACC formula previously shown.

3.39 Data used for calculating the expected return on equity (ROE) is shown in Table 3-6. Also refer to the description of the calculation of cost of debt later in this chapter.

Table 3-6: Expected Return on Equity (ROE) using the CAPM for Three New York Stock Exchange Shipping Companies

	Co. A	Co. B	Co. C
Riskless Rate (Ibbotson)	3.0%	3.0%	3.0%
Equity Premium (Ibbotson)	6.67%	6.67%	6.67%
Beta (Yahoo)	1.40	3.21	0.97
Size Premium	1.69%	1.69%	0.74%
Industry Premium	1.32%	1.32%	1.32%
ROE	15.35%	27.42%	11.53%

3.40 The ROE calculated using the CAPM analysis shown in Table 3-6 is heavily dependent on the beta used. Beta is a statistical measure of the variability in market price in correlation with the total observed market. Betas from Yahoo Finance were used. Ibbotson Associates advises that very high betas are "not specifically meaningful" (e.g., the Co. B's beta of 3.21). Viewed as a group the average cost of equity is approximately 18 percent.

3.41 The final step in the company specific analysis is to calculate the WACC for each company using the previously shown formula for calculating the WACC. The WACCs for the three companies are 10.5% (Co. A), 12.510% (Co. B), and 9.0% (Co. C). The average of the three companies is approximately 10.5%.

3.42 The final step in the company specific analysis is to calculate the WACC for each company using the previously shown formula for calculating the WACC. The WACCs for the three companies are 10.5 percent (OSG), 12.5 percent (Navios), and 9.0 percent (Teekay). The average of the three companies is approximately 10.5 percent

3.43 Based on the estimated WACC for the deep sea foreign transportation of freight industry (SIC Code 441) of 9.5 percent and calculation of specific shipping company WACCs of 10.5 percent, a 10 percent discount rate appears to be appropriate for the marginal abatement cost analysis.

Sensitivity Analysis

3.44 Our analysis looks at the sensitivity to the calculations of various inputs. The low case for the discount rate would be the calculated 4.0-4.5 percent "risk free" maritime rate based on the U.S. treasury rate plus a 1.0 percent "securitization" premium (as described previously). The high case for a discount rate is derived based on the calculated average cost of equity for maritime firms of 18.0 percent (as described previously). For the sensitivity analysis, the "risk free" discount rate at 4.0 % for the securitization transactions in the maritime shipping industry is used as the low bound estimate; the 18%, which is the cost of equity, is used as the high bound estimate.

Net Present Value Analysis

3.45 For evaluating the MAC for each abatement type we used a Net Present Value analysis taking into account the time value of money. We also used a version of net present value analysis, called equivalent annual cost, to spread capital costs over a specified time horizon. In our case this works out to be the equivalent of an annuity of N years yielding a 10.0 percent return (in the base case – we assume the ship-owner has a marginal tax rate of near zero – similar to a tonnage tax system).

Opportunity Cost of Vessel Capacity/Time

3.46 If a vessel is taken out of service to install an energy-efficiency improving technology w assumed that there is a lost opportunity cost for the time the vessel is out of service. Similarly, to retrofit an existing vessel some technical measures require some extra days beyond the regular dry docking. The costs of this extra time were assumed to be 75% of the term-charter rate, which are discussed in the next section. The extra days assumed in this study are listed in Table 3-7.

Table 3-7: Extra dry docking days of some retrofitting measures

	Low Estimate	High Estimates
Wind Engine	2	7
Towing Kite	0	2
Solar Power	0	2
Main Engine Tuning	0	2
Common Rail Upgrade	0	2
Air lubrication	0	2
Boss Cap Fin	0	2
Optimization Water Flow	0	2
Speed Control Pumps	0	2
Hull Coatings	0	3

Term-Charter Rates

3.47 Term charter rates were examined from various sources including Clarksons Research Services Shipping Intelligence Network, Fearnleys, BRS Salles, UNCTAD, and interviews with industry sources for estimates for ship types that have not been contracted recently. When available, we used one-year term charter rates averaged over the January 2000 through May 2010 period to smooth the yearly fluctuations. This gave us a "long term" average term charter rate that tended to represent a full shipping industry cycle as opposed to a single point in the industry cycle.

3.48 Unfortunately, many of the ship types did not have charter rates available on a "reliable" basis. Our approach for determining those rates was to find current new-build costs and determine a bareboat-equivalent charter rate (basically a 30 year annuity at a 10 percent discount rate assuming a zero marginal tax rate – note scrap value would have a minimal impact on a 30 year time horizon with a 10 percent discount rate). For ships that had not been contracted to build recently or if that information was not available we used two approaches to estimating the costs. We contacted industry experts for their opinions and we made estimates based on the gross tonnage of the average vessel in the size class and used a similar size vessels new-build cost (for which we had data) adjusted based on the ratio of compensated gross tonnage (source: OECD Compensated Gross Ton (CGT) System 2007). This enabled us to estimate bareboat-equivalent charter rates for each IMO ship type and size. This is roughly equivalent to a replacement-cost valuation approach. To this bareboat-equivalent rate we added current ship operating costs (Drewry, 2009) to arrive at an estimated term charter rate. Drewry only provides ship operating costs for a limited number of the IMO ship classes. The other ship classes were estimated based on ship type, size and complexity of operations.

3.49 The accuracy of this analysis was tested by comparing the term charter rates for the available ship sizes and types (e.g., crude tankers, bulkers, and containerships) with the calculated term charter rates for the same ship type and size based on the bareboat equivalent analysis. The results were reasonably consistent.

Vessel-Age Analysis

3.50 Vessel ship age plays an important role in determining the cost of a certain technology or operational option. The costs of fuel-efficiency improvement options may vary significantly for ships of different ages, especially when the economic life of the technology is close to or more than the remaining life of the vessel. Therefore, taking ship age into consideration can improve the quality estimates of cost effectiveness. The age analysis performed was based on the Lloyds Register/Fairplay Sea-Web ship database. For each IMO ship type (and size information) for each vessel classified as "in service" data was downloaded (June 2010) and averages were developed for each IMO ship type, size, and age category. We use six age categories of five years each.

3.51 In this report, the lifetime of the ship was assumed to be 30 years. This assumption is consistent with the seven-year average of ship broken-up ages from the UNCTAD's Review of Maritime Transport (Table 3-8).

Table 3-8: Average age of broken-up (Source: Review of Maritime Transport, various issues)

Year	Tanker	Dry Bulk	Container	General Cargo
2001	28	26.7	26.9	27.4
2002	28.3	26.6	26	28.2
2003	29.3	26.5	25.5	29.3
2004	29.5	27.3	30.5	32.9
2005	31.5	28.1	30.6	31.9
2006	30	28.9	28.1	32.3
2007	31.4	29.1	29.6	34.9
Seven years average	29.7	27.6	28.2	31.0

3.52 Ship category changes over the year. In 2020, ships younger than 13 years will remain in service, but they are in different age categories. Ships that fell into the category of 17.5 years old, 22.5 years old, and 27.5 years old will be replaced by new ships. In 2030, only ships younger than 23 years in 2007 will be in service, and all other ships are replaced by new ships. The changes of age categories are shown in Table 3-9.

Table 3-9: Ship Categories Changes

Ship ages in 2007	2007	2020	2030
Younger than 5	2	15	25
Between 5 and 9	7	20	0
Between 10 and 14	12	25	5
Between 15 and 19	17	0	10
Between 20 and 24	22	5	15
Older than 25	27	10	20

3.53 All ships, no matter how many years of remaining service life, are assumed to use energy-efficiency improvement technologies and operational options. We did not assume that ships whose remaining lifetime is shorter than the energy-efficiency improvement measure would not use such a measure. Rather, we calculated the MAC for all the age groups.

Technology Learning Curve

3.54 When a new technology is introduced there is usually a "learning curve" that over time yields cost reductions. This learning curve can occur for several reasons. Companies may become more efficient in the production/delivery of the technology or achieve economies of scale as production volumes increase. Sometimes it comes about through competition (Ghemawat, 1985). Whatever the cause, it is widely established that the introduction of new technology usually sees the price fall over time. The challenge in determining the marginal abatement cost is to estimate just what the learning curve impact will be on the cost of new technology introduced to the maritime industry. The learning curve may be driven by physical constraints (e.g., the introduction of VLCCs was initially constrained by the ability of shipyards to accommodate the size of the ship). In this case we anticipate that the learning curve will come about through experience and production efficiency improvements. The learning curve will vary with the type of technology. For example, electronic technology type innovations will probably go through a relatively quick learning curve. Modifications to hull forms will probably take longer to develop.

3.55 The U.S. National Aeronautics and Space Administration (NASA) also provided information on learning curve effects in various industries including the maritime industry on their website (see http://cost.jsc.nasa.gov/learn.html). The shipbuilding learning effect is identified as 80 to 85 percent. In comparison, aerospace has a learning effect of 85 percent and repetitive electronics has a learning effect of 90 to 95 percent. The NASA approach is based on the number of units produced. In general, the NASA learning curve impact is approximately 15 to 20 percent in total.

3.56 The approach to estimating a maritime industry learning curve adopted in this study is based on the learning curve associated with the introduction of double-hull tankers following the passage in the United States of the Oil Pollution Act of 1990 (OPA 90) and subsequently spread worldwide through the IMO and its Amendments to Annex 1 of MARPOL 73/78 Regulations 13F and 13G (now Regulations 19 and 20).

3.57 The cost of a new AFRAmax tanker (80k – 120k DWT) was examined in comparison to the cost of a new handy size bulker during the 1979 through 2009 period with particular attention focused on the 1990 to 1995 period to see how the cost (price) of a double-hull tanker evolved. Other cost influencing factors (e.g., wage rates, steel costs, shipyard competition) are accounted for by examining the tanker cost relative to a bulkers cost. New-building costs for an AFRAmax tanker and Handy size bulker are shown in Table 3-10.

Table 3-10: New-building Costs: AFRAmax Double- Hull Tanker and Handy Size Bulker ($ millions) (Source: Clarkson's Shipping Intelligence Network)

Year	AFRAmax	Bulker
1990	$53.0	$21.0
1991	$52.0	$22.0
1992	$48.0	$20.0
1993	$44.0	$21.0
1994	$41.0	$19.0

3.58 The change in the ratio of the AFRAmax tanker cost to the Bulker new-buildings will indicate the degree and speed of the learning curve. This relationship is shown in Figure 3-2 (normalized to 1993 at 1.00).

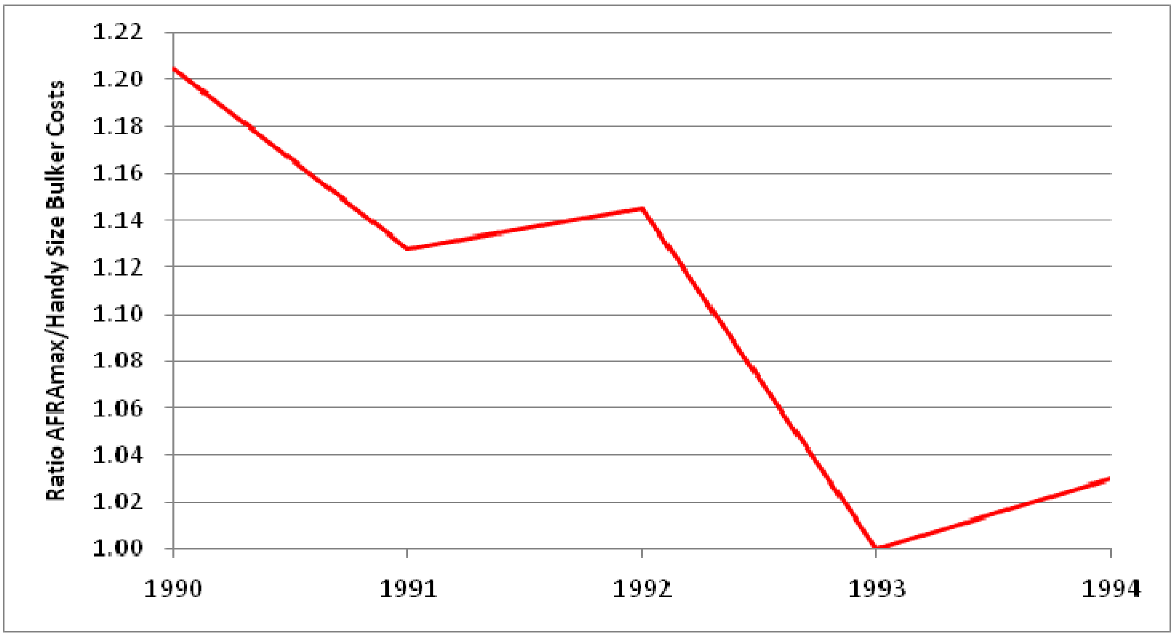

Figure 3-2: Relative Newbuilding Costs AFRAmax Double-Hull Tanker and Handy Size Bulker (tanker/Bulker normalized to 1993=1.00)

3.59 As shown in Figure 3-2, the initial cost of double-hull AFRAmax tankers was approximately 20 percent higher than the longer-term cost in 1993/1994 period. Over time the ratio of AFRAmax tanker to handysize bulker new-building costs have varied significantly. During the period 1979 to 1989 the cost ratio (normalized to 1993=1.00) was 0.95. During the period 1993 to 2009 the cost ratio averaged 1.10. This indicates that double-hulling increased the cost of a tanker on the order of 15%. This is consistent with the estimated cost increase for tankers developed in the 1998 report "Double-Hull Tanker Legislation" produced by the National Academy of Science's Marine Board committee examining the impact of U.S. Oil Pollution Act of 1990 (OPA-90) on the tanker industry. It is also consistent with the "OPA 90 Programmatic Regulatory Assessment (PRA)" produced in May 2001 by the US Department of Transportation's Volpe National Transportation System Center's Economic Analysis Division. This suggests that the 20% decline from 1990 to 1993 may overstate the learning curve effect. Accordingly an overall 10% learning curve rate was selected (the first year price increase of 25 percent eventually declined to a long-term average 15%).

3.60 Based on this analysis, a maritime industry learning curve for new technology was established as follows: for the first five years, cost is reduced by 10%. After the fifth year, the learning rate is assumed to run out. This figure is within reasonable range with the learning rate used by NASA in the shipping industry.

3.61 We offer one caveat. Most technologies have been proposed since 1970s. In other words, these technologies are not new. The learning rate that can be achieved is limited. Assuming cost reductions in the next few years for these mature technologies risks underestimating their costs. Therefore, we apply the learning rate to only five technologies: air lubrication, waste heat recovery, wind engine, wind kite, and solar energy. For air lubrication and waste heat recovery, the 10% learning rate is used. For wind engine, wind kite, and solar energy, the learning rates of onshore wind solar energy are used. For these three technologies, a 15% learning rate is used.

CHAPTER 4

BARRIERS TO IMPROVING SHIPBOARD ENERGY EFFICIENCY

4.1 In this chapter the barriers to implementing shipboard energy improvements are examined. Broadly speaking, the barriers to implementing technical and operational measures that reduce energy consumption by ships can be divided into technology constraints and non-technology constraints, which are institutional and financial. The non-technology constraints that prevent the adoption of technical and operational measures to increase the energy efficiency could potentially be resolved through economic and/or regulatory policy instruments, at least theoretically. Whereas, technology constraints can only be resolved through technological breakthroughs.

4.2 When considering the barriers to introduction/expanded use it is worth noting that almost all of the current proposed approaches to shipboard energy efficiency improvement being discussed were being proposed and/or tried back in the late 1970s / early 1980s (if not a lot earlier) in response to the oil price increases at that time.[4] There were numerous reasons why these proposed approaches were or were not fully exploited. Those same barriers to implementation are at work today. Issues such as technical concerns regarding the reliability of the approach in the maritime environment, over stated benefit claims, market issues, and economics were some of the common barriers.

4.3 Many of the proposed approaches (as proposed in the 1970s and still being put forth as "proposed" approaches today) were implemented (e.g., hull cleaning, propeller polishing, weather routing, auto-pilot optimization, etc.). Therefore, consideration of the current penetration of the proposed approach needs to be taken into account when considering the overall impact of the approach on maritime industry's fuel consumption. For example, propeller polishing may improve propulsive efficiency (i.e., fuel consumption) by up to five percent over an in service propeller that has never been polished. However, numerous vessel operators polish their propellers on a regular basis. Thus, it is unlikely that propeller polishing will provide industry wide fuel savings of five percent because a significant portion of the fleet has already implemented that approach.

4.4 The barriers identified, from prior introduction experience and current analysis, fall into three broad categories as follows:

.1 Technological – Concerns over the ability of the energy efficiency improvement approach to work (particularly in the marine environment) and/or provide the claimed benefits or if the approach requires the installation of equipment that would interfere with the normal working of the ship (e.g., cargo handling or stowage).

.2 Institutional – Regulatory and/or commercial arrangements that serve to impede the introduction and/or expanded use of the energy efficiency improvement approach.

.3 Financial – Some approaches are only financially viable (i.e., providing a positive net present value) when oil prices reach a specific level and are expected to stay above a specific level long enough to provide an adequate financial return on the investment in the energy efficiency improvement approach.

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[4] See "Maritime Fuel Conservation" by E.V. Lewis, et al, the Society of Naval Architects and Marine Engineers (SNAME) Transactions 1977 available at www.sname.org

4.5 Each of these types of barriers is described in greater detail in the balance of this chapter.

Technological Barriers

4.6 The technological barriers may be real or perceived. For example, wide spread reporting of a failure of an early installation (test or not) can delay future implementation. Reported problems with the early large size azimuth pods on several cruise ships, including the Queen Mary 2, may cause shipowners to delay investing in the technology. Similarly, contra-rotating propellers have also been "labelled" as having bearing problems. The vessel type can impact the ability to install certain fuel saving approaches. For example, wind engines, such as a Flettner rotor, require a lot of deck space for installation. However, container ships and dry bulkers require large, removable hatch covers for access to cargo holds. Therefore, the deck space is not available for the installation of a wind engine. This report has evaluated the applicability of all measures to ships, taking into account the ship type, size and age. More details on technical barriers and limitations of specific technologies can be found in Chapter 5.

4.7 Another issue to consider is that certain approaches are mutually exclusive or are only applicable to certain types of ships. This is best understood through a brief description of ship resistance, which determines engine power requirements and fuel consumption. In general, ship resistance is composed of frictional resistance (between water and the ship's hull) and wave making resistance. As vessel speed increases the wave making resistance increases and becomes a greater percentage of total ship resistance. The wave making resistance is related to the natural period of the wave generated as the vessel moves through the water. All else equal, the longer the ship the longer the wave generated which has a higher natural frequency and, therefore, lower wave making resistance (because the longer ship generated wave wants to move faster). For comparison purposes, wave making resistance is roughly proportional to the speed length ratio (ship speed divided by the square root of its length[5] although the more complex Froude number is a better comparison). For vessels with higher speed-length ratios (e.g., containerships, RO-ROs, cruise ships, etc.) approaches directed at wave making resistance (e.g., bulbous bows, optimizing hull configuration, etc.) will have greater impact. Conversely, vessels with relatively low speed-length ratios (VLCCs, Capesize bulkers, etc.) will benefit more from approaches to reducing frictional resistance (e.g., hull cleaning, air cavity, etc.). Therefore, for example, implementing vessel speed reduction will reduce the benefits of an approach that targets reducing wave making resistance.

Institutional Barriers

4.8 Perhaps one of the biggest institutional barriers to implementing fuel saving projects that require capital investments (e.g., waste heat recovery systems) is the divided responsibility or "split incentive" between shipowner and charterer for fuel costs. Ships are typically hired (chartered) in one of the four manners listed below:

.1 Spot or voyage charter – the shipowner agrees to move a specific cargo on a specific ship from port A to port B. In this arrangement the shipowner is responsible for all vessel and voyage costs.[6]

5 Length used is length on waterline which is closest to length between perpendiculars (LBP) of the normally reported ship lengths, as opposed to length overall (LOA).

6 Vessel costs include crew, maintenance & repair, insurance, and capital costs. Voyage costs include fuel, port (tugs, dockage, harbour fees, etc.), and canal costs.

.2 Term or time charters – the shipowner provides a specific fully manned vessel to the charterer for a fixed amount of time (typically six months to five years). The shipowner pays the vessel costs and the charterer pays the voyage costs.

.3 Bare boat charters – a shipowner provides a specific ship without crew to the charterer. The charterer is responsible for vessel (except capital) and voyage costs. Bareboat charterers are common in lease financing arrangements.

.4 Contracts of Affreightment (COAs) – a shipowner agrees to move a specific amount of cargo over a specific time from port A to port B without specifying the ship. The shipowner pays vessel and voyage costs. Because COAs may cover a longer time frame (one or more years) they will sometimes have bunker escalation clauses in which the freight rate is adjusted to cover higher than "base" fuel costs.

4.9 The split incentive refers to a situation in which the people benefiting from energy efficiency are not the people paying for it (Jaff *et a*l, 1994). In the shipping industry, it occurs when there is a disconnect between the vessel owner, who controls capital spending and energy conservation efforts, and the operator, who is responsible for fuel cost (CE Delft, 2009). This primarily occurs when vessels—especially bulk carriers, tankers, and containerships—are hired under contract for a limited period of time (known as a "time charter"), or when only the vessel but not the crew is hired (known as a "bareboat charter") (Wijnolst *et al*, 1997).In such cases, it is the charterer who pays for fuel but the ship owner who is responsible for any investment in energy-efficiency equipment.

4.10 Ships that are more energy efficient could theoretically have higher charter rates in the market (AEA, 2008), in practice this is difficult due to the diversity of the charter market of the difficulty "guaranteeing" an improved fuel consumption on a vessel whose speed is heavily impacted by the vagaries of sea conditions (e.g., weather). However, most of the major charterers are basing hire decisions on notional voyage economics and, therefore, are taking fuel consumption/speed guarantees into account in the hire decision.

4.11 Some economically viable fuel-saving efforts are route-specific and influenced by other factors (e.g., wave and weather conditions). Real fuel savings are very difficult to predict, hence a charterer is unlikely to pay a premium without a fuel-saving guarantee.

4.12 Shipowners[7] will typically employ their vessels in a mix of spot and term charters. A shipowner only bears full responsibility for fuel costs in spot voyage charters. The current chartering system typically has "industry standard" speed and fuel consumption guarantees, therefore, in a term charter the shipowner may not receive a "premium" for a ship that is more fuel efficient than the "industry standard." This reduces the incentive for a shipowner to make a capital investment in a fuel saving approach as the benefits (fuel cost savings) will not necessarily accrue to the shipowner. Recently, however, the trend in the industry is towards recognizing the value in energy efficient ships.

4.13 Another issue is that shipowners do not typically expect to own a vessel for its entire life. This can limit the time over which a shipowner is willing to include fuel cost saving benefits in analyzing the investment in a fuel saving approach. It is not guaranteed that shipowners can obtain a premium for a ship in a second hand sale that has better than expected fuel efficiency (or that the buyer will view the benefit of reduced fuel consumption

[7] The term "shipowner" is used in this chapter to refer to the actual vessel owner. It is not uncommon for a company to time charter a vessel for the sole purpose of performing spot charters for other charterers.

in the same manner as the seller). This may have the added impact of causing shipowners to evaluate investments in energy saving equipment using a "payback" period approach instead of the more accurate net present value approach (Brealey *et al*, 2005)

4.14 In liner shipping, tramp contracts, cruise lines, and RoPax ferries, freight rates sometimes include fuel surcharges (CE Delft, 2009). These pass at least part of the fuel costs on to consumers, another form of split incentive.[8]

4.15 Another chartering related barrier to fuel savings occurs when a vessel on a spot charter is moving to a discharge port with a known congestion or other problem that will delay the berthing of the vessel when it reaches the port. Under the current system, the shipowner is responsible if the vessel arrives outside of the originally designated discharge window (although the charterer has little actual recourse against the shipowner). If the vessel sails at normal speed to the discharge port and arrives within the designated window but the terminal is not ready to discharge the cargo, the time counts as "laytime" and once the specified allowed laytime is exceeded, the charterer must pay the shipowner "demurrage" at a rate (typically US$s per day or fraction thereof) specified in the charter. The opportunity to save fuel by sailing slower and arriving when the berth is ready for the vessel is lost in the current system. To address this issue, INTERTANKO, the shipowners' association of independent (i.e., non-oil company) tanker owners, and OCIMF (Oil Companies International Marine Forum) have developed an approach called "Virtual Arrival"[9] that seeks to remove the barrier to slow down operations under a spot charter arrangement. *Virtual Arrival*, can show how the shipowner-charterer problem costs the industry and how the energy efficiency will be improved if the problem could be resolved. Early trials have resulted in significant savings, in one case a 27% reduction in fuel costs were found. *Virtual Arrival* requires inclusion of the specific agreement in the charter party and includes demurrage compensation for the added time related to slower steaming for the shipowner and shared benefits between the shipowner and charterer for reduced fuel consumption. It remains to be seen if this approach will succeed but it demonstrates the concern by the industry regarding the institutional barriers to one of the most effective fuel saving approaches (Intertanko, 2009).

4.16 Implementing slower speed operation of a ship is a trade-off between the fuel cost savings and the cost of additional ships to replace the vessel capacity lost with slower sailing speeds. Typically, slow down is implemented when there is the combination of high fuel prices 1970s / early 1980s in the tanker industry. At least one major oil company operated its long-haul crude oil fleet (owned and time chartered) in slow down mode to reduce overall shipping costs.

4.17 The same situation has emerged in the international container (liner) shipping industry beginning in late 2008. Fuel costs are relatively high combined with relatively low charter rates brought on by reduction in demand and the delivery of a large number of containerships ordered barriers to implementing slower vessel operations are arising in the container shipping industry. Shippers of containers (e.g., large box retail stores) have seen impacts on their supply chains of longer transit times and are resisting changes to slower speeds (i.e., longer transit times).

4.18 Another potential barrier to reduced speed operation is an emerging shortage of seafarers. This may push vessels back to full speed to maximize deliverability and minimize the number of crew required.

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8 In economics this is known as the "principal-agent problem" and is a special case of the split incentive. This refers to the situation that the interests of the principal and agent differ substantially. The charter agreement exhibits a classic example of the principle-agent problem.

9 See "Virtual Arrival – a way to reduce greenhouse gas (GHG) emissions" by Erik Ranheim (INTERTANKO) and Garry Hallet (OCIMF) 2 March 2010

4.19 There are also regulatory barriers to employing certain fuel saving approaches. For example, in ports in California hull cleaning is not allowed in State waters (within three miles of shore) if the vessel has certain types of hull coatings that have been determined by the State to harm the environment (the hull cleaning residue is released into the water surrounding the vessel). This forces the operation offshore that significantly increases the cost.

4.20 Just as regulatory barriers can serve as a barrier to implementation of an energy efficiency improvement, governments have introduced incentives to improve the energy efficiency of vessels. For example, one consultant whose firm participated in repowering about 40 domestic vessels and convert both 4-stroke and 2-stroke mechanically injected engines to electronically controlled engines estimated that these refits had payback periods of 15 to 20 years in most cases, with the returns coming primarily from fuel savings and secondarily from relatively small maintenance cost improvements. To provide financial incentive to repower their ships and achieve emission related offsets in the Port of NY/NJ, the U.S. EPA and the Port Authority of New York and New Jersey funded most of these projects under programs that paid for nearly 100% of the cost of the new engines, while the vessel owners covered the costs associated with installation resulting in approximately 65% to 75% of the total project being funded[10]. With these incentives the payback periods, based on current fuel costs, were in the four- to seven-year range. Even a four-year payback time is insufficient incentive to many ship owners.

4.21 The Ports of Los Angeles and Long Beach and the State of California have similar programs for assisting harbor vessel owners to re-power with lower emission engines.

Financial Barriers

4.22 In order to invest in energy saving approaches shipowners expect to receive a financial benefit that earns them a risk adjusted rate of return on the investment. Many energy saving approaches have been rejected because of low expected returns on the investment. The "benefit" that offsets the cost of the investment is future reduced fuel costs. Future reduced fuel costs involves savings in fuel consumption (tons or barrels per day) and the cost of the fuel (US$s per ton or barrel). Fuel costs fluctuate significantly.Within the last few years crude oil prices have ranged from nearly $150 per barrel to as low as $40 per barrel. Residual and diesel fuels have had similar variations as shown in Figure 4-1. Fuel costs, therefore, insert significant uncertainty (i.e., risk or "uncertain price signals") into an investment in a shipboard energy efficiency improvement investment. This has served as a barrier in the past, for example, waste heat recovery systems were not perceived as having a positive net present value when considered in the late 1970s / early 1980s.

10 Based on an interview with an anonymous consultant who helps the EPA and Port Authority of New York and New Jersey to repower ships.

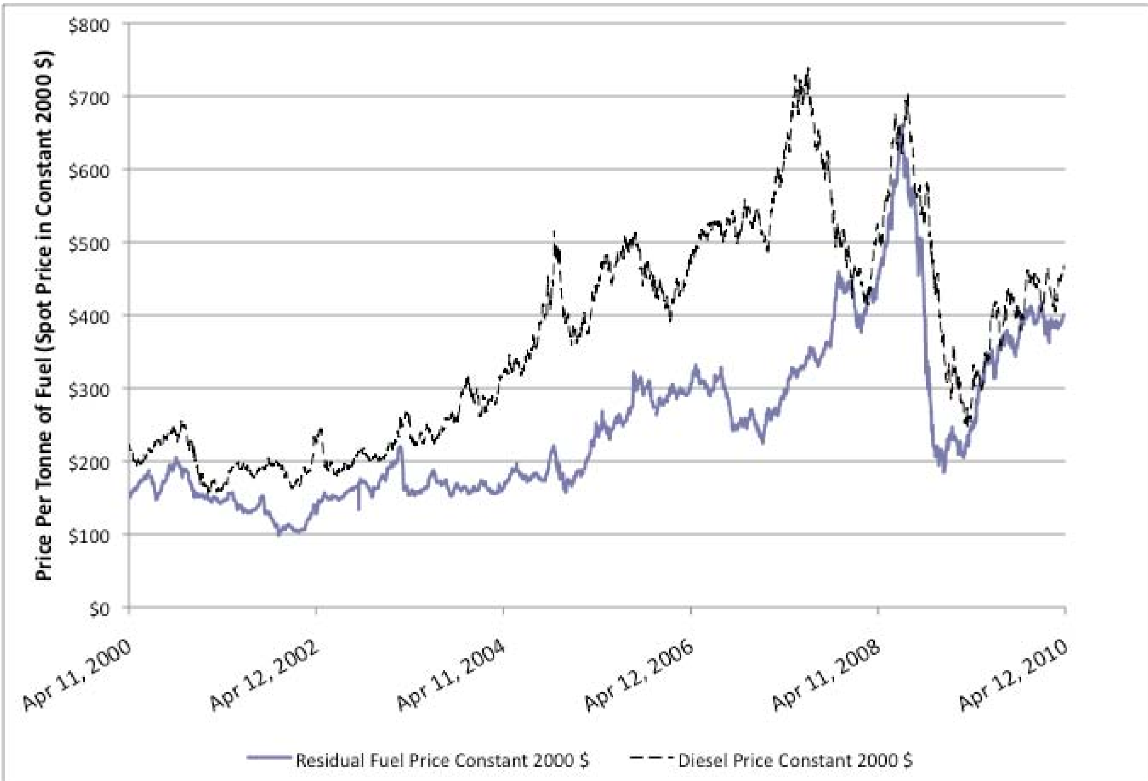

Figure 4-1: Fuel price in the recent decade (Date Source: www.iea.gov)

4.23 Another rather obvious barrier is related to shipping market cycles. Virtually all sectors of the shipping industry go through "boom/bust" cycles. During "boom" times, when profits are high, shipowners have the funds to make investments in energy saving technology. However, shipowners are reluctant to take a vessel out of service (and miss out on high freight rates) for more than the minimum regulatory period[11] and may not make investments that will increase the time out of service. During the "bust" part of the cycle, when profits are low, shipowners are reluctant to make investments and may not have access to the capital required for the investment. The "boom/bust" cycle issue may have a different impact in that an energy saving approach, during the "boom" part of the cycle may be used to increase the speed of the vessel rather than reduce its fuel consumption. For example, if a shipowner cleans the hull of a ship, one of two things will occur. The shipowner will either continue to operate the main engine at the same power level resulting in a small increase in speed due to the reduced resistance of the hull or the shipowner will reduce the power (operating RPM) level of the main engine to maintain the same pre-cleaning speed resulting in reduced fuel consumption. It has typically been the former resulting in increased speed or, as a shipowner would say, "return to design speed." It is also possible that a small shipowner will not be able to obtain financing for the capital costs of an energy-efficiency improvement measure.

4.24 If a vessel is designed for a particular route, on which it will operate for the majority of its lifetime, then optimizing energy-efficiency using specific technologies is easier. However, most ships are used on many different routes under varying physical conditions, which makes the benefit of any given technology hard to assess. Given the need for "flexible" vessels, trading along different trade routes leads to design and construction of

[11] Currently, most ships are required to be drydocked twice in a five year period with no more than three years between drydocking. There is some flexibility in this rule with underwater surveys allowed in some cases but not for tankers or bulkers over 15 years old. There has been some movement to a seven and a half year drydock cycle. See "Pilot Program for Extended Survey Periods" in Activities May 2010 published by the American Bureau of Shipping (ABS)

ships that are not necessarily "optimized" for specific voyages. Within each size category of vessels (e.g., AFRAmax and SuezMAX tankers), ships have been growing in size but it is lot clear that they are carrying larger parcels of cargo (i.e., they are not sailing fully loaded). The size of the parcel is determined between the buyer and the seller of the cargo. The ship is selected based upon the ability to load the full cargo but not necessarily to fill the ship. Filling a larger ship or using a smaller ship loaded fully would be more fuel efficient. However, the current commodities trading market does not fully integrate vessel fuel efficiency into its trading patterns.

Conclusions

4.25 There are numerous barriers to the implementation of a more fuel efficient global shipping fleet. As described, some of the barriers are technical in nature and many of them are institutional in nature. In the end most of the barriers are of a financial nature. Institutional barriers have a way of falling when the economics are favourable, or when there are specific regulatory requirements that necessitate or foster change.

CHAPTER 5

ABATEMENT MEASURES

5.1 This study identified some 50 operational and technological measures to reduce CO_2 emissions from maritime transport. This chapter describes the allocation of these measures to different groups and it describes the measures by those groups. On about 20 measures, we have been able to get data on costs and abatement potentials. Measures have been compiled from several sources, building on previous compilations literature (Buhaug *et al*, 2009; CE Delft, 2009; Crist, 2009). We attempted to corroborate this data with direct interviews of operators and others with experience with the measures. However, further work needs to be done on the actual in-service cost, reliability, variability, and effectiveness of these measures. SNAME's Technical & Research Committee will continue to evaluate these measures.

A Brief Discussion of the Energy Efficiency Design Index

5.2 The following is a discussion of the EEDI and the potential impact on MAC and implementation of abatement measures. An expanded discussion is in Appendix I.

5.3 The IMO's Marine Environment Protection Committee (MEPC 60) released "Interim Guidelines on the Method of Calculation of the Energy Efficiency Design Index for New Ships" (EEDI). At this time, EEDI is still under consideration although it is well along the development process. It is designed to provide a formula for a consistent approach to measuring the energy efficiency of a vessel as it is put into service (i.e., as-built). It is intended to provide a baseline for future use in a GHG emission reduction system. There are concerns that the formulaic approach may lead to unintended consequences. There have been research papers developed expressing some concerns over a "one size fits all approach." The EEDI formula is explained in more detail in Appendix I to this report.

5.4 EEDI has in its numerator factors related to the fuel consumption of a ship (main engine size and efficiency, auxiliary engine size and efficiency, waste heat and shaft generator capacity and efficiency, and other design options). The denominator is comprised of vessel deliverability (capacity and speed) and weather factors.

5.5 Just as the naval architecture profession has evolved to provide individuals with specific expertise and creativity to design vessels to obtain desirable vessel tonnages under the admeasurement rules[12], there will likely emerge specialists on the EEDI formula when it becomes mandatory. The question then becomes, how can these future specialists optimize and "game" the formula to provide their clients favourable treatment under the system.

5.6 Several things are important to understand regarding the current (June 25, 2010) state of the EEDI formula including:

.1 Efficiency gains through hull optimization and propeller improvements are captured in the formula through lower installed power (because the hull has lower resistance or the propeller is more efficient it takes less installed power to achieve the design speed).

[12] Admeasurement rules define gross and net tonnages for vessels based on cargo holds, enclosed spaces, etc. and create highly complex design and building issues that impact vessel regulatory requirements as well as canal and port fees.

.2 The denominator has design cargo capacity (e.g., 65% of DWT for containerships) and vessel design speed.

.3 Several of the factors for such things as waste heat recovery, efficient design options, impact on speed of sea conditions are not clearly quantified at this time.

.4 Recent interest and studies in ships' aerodynamics indicate that there is the potential for reduced drag, albeit small relative to potential hydrodynamic efficiencies.

5.7 The main issue regarding EEDI and this research effort is how the formulaic approach will impact the introduction of energy efficiency improvement approaches. The development of the factors relating to waste heat and shaft generators will impact the penetration rates for those systems. Ship speeds that are currently based on market requirements may well be lower to reduce the EEDI result. Similarly, vessel capacity may be adjusted to improve an EEDI rating.

5.8 A lot of the focus to date has been on the impact of vessel speed on EEDI. Perhaps cargo capacity will be just as big an issue. Cargo capacity is generally defined by the load lines established for a ship. Load lines are based on freeboard requirements and watertight deck levels as established under IMO's Load Lines Protocol conventions. Currently numerous vessels trade with multiple load lines so as to qualify to trade into deadweight restricted areas (e.g., the Puget Sound has a 125,000 deadweight limit). It is easy to alter deadweight by having an additional load line assigned that complies with freeboard requirements (freeboard requirements establish a "minimum" requirement that must be met or *exceeded*). It is conceivable that vessel depth will be altered in such a way as to increase the freeboard and create an increased EEDI rating.

5.9 One of the biggest concerns with EEDI is that the most direct way to capture efficiency gains through hull/propeller optimization is by installing smaller engines (i.e., reduced horsepower) as EEDI is based on the Maximum Continuous Rating (MCR) of the main engines. Installing lower horsepower main engines may reduce the safety margin for vessels operating in heavy seas. This can be addressed by de-rating more powerful engines or using engines that can deactivate cylinders (so as to have available reserve power for safety considerations). There have been discussions regarding allowing "CSR-based[13]" main engine horsepower (e.g., design horsepower instead of installed horsepower) to be used instead of MCR-based main engine horsepower.

5.10 The following is an example of how the designer can optimize the EEDI with the application of a hull coating that can improve energy efficiency. During the design phase, the designer may specify that a specific hull coating be applied. The net improvement in energy efficiency by the specification of the hull coating could translate into an optimized EEDI through the installation of a smaller engine. If applied after design but prior to the sea trial, this could result in a higher design speed at the installed engines power rating, thus reducing the vessel's attained EEDI.

5.11 This will introduce a whole new vehicle for optimizing designs for energy efficiency as well as for "gaming" the EEDI rating.

[13] The CSR-based (continuous service rating) horsepower would be the maximum horsepower allowed under non-emergency operations and would be used in the EEDI formula.

Grouping of abatement measures

5.12 Setting up a marginal abatement cost curve, some of the individual abatement measures that are accounted for may exclude each other in the sense that these measures cannot/will not be applied at the same time. Therefore it is useful to subsume the individual abatement options to groups, whereas the measures that exclude each other are being allocated to the very same group, and to ultimately present the marginal abatement cost curve on an option-group-basis.

5.13 The most obvious reason why abatement options should be considered to exclude each other is when these measures aim at reducing the energy loss of a vessel in the same way and no extra abatement can be expected from combining these options. There will, for example, be no extra emission reduction from cleaning a hull that has just been blasted. However, a combination of such measures may make sense when the options are applied at different points in time. When, for example, a hull is coated every 5 years, cleaning the hull additionally, in between these five years, will lead to extra emission savings. That is why hull cleaning and blasting are allocated to the same group whereas hull coating is allocated to a separate group.

5.14 Another reason why abatement options should be considered as excluding each other is that a combination of these measures would not be feasible due to practical reasons. For instance, two technical options that require a lot of deck space or two options whose combination might turn out to be counterproductive or may even constitute a safety hazard due to unpredictable interactions have to be classified as mutually exclusive too. The combination of a towing kite and wind engines is an example for two options that for practical reasons are allocated to the same option group.

5.15 Retrofit abatement options and options that can only be applied to new-builds are taken to be both applicable to new-builds and are thus, when they can be combined, allocated to different groups. When a retrofit option and a non-retrofit option exclude each other and are thus allocated to the same group it should be borne in mind that only a subgroup of options, the retrofit options, are relevant for ships that already are in the market.

5.16 Taking these considerations into account, the individual measures are allocated to the following 29 measure groups as shown in the following table; 8 groups with operational and 21 groups with technological measures[14]. When a group contains more than one measure, an umbrella term is chosen for the group. An 'R' or 'N' in brackets indicates whether a technological measure can be retrofitted or only be applied to new-builds.

[14] Since the use of a bulbous bow does only lead to fuel savings when the ship is operated at its design speed, speed reduction (an operational measures), and the use of bulbous bow, (a technological measure), are allocated to the same measures group.

Table 5-1: Proposal for a grouping of the individual emission abatement options

	Measure group			
Operational options	Operational speed reduction	Speed reduction	Voyage optimization, including reduced port time	Bulbous bow (R)
	Optimization of ballast and trim			
	Efficiency of scale	Using larger existing ships	Increasing cargo load factor	
	Weather routing			
	Autopilot upgrade/adjustment			
	Increasing energy awareness (hotel services)			
	Propeller maintenance	Propeller polishing (at regular intervals)	Propeller polishing when required (including monitoring)	
	Hull cleaning			
Technological options	Lightweight construction (N)			
	Optimization hull dimensions	Optimum hull dimensions (N)	Aft waterline extension (R)	
	Efficiency of scale (building larger ships) (N)			
	Hull coating	Hull coating I (R)	Hull coating II (R)	
	Optimization hull openings	Low-profile hull openings (N)	Optimization water flow of hull openings (grids, scallop) (R)	Covering hull openings (R)
	Design speed reduction	Smaller engine (N)	Speed reduction and engine de-rating (R)	
	Optimization propeller-hull interface	Optimal propeller-hull interaction (N)	Skeg shape/trailing edge (N)	Interceptor trim plates (R)
	Air lubrication (N)			

	Propulsion upgrade I	Propeller-rudder upgrade (change of rudder profile and propeller) (R)	Propeller upgrade (nozzle, tip winglets) (R)	Propeller boss cap fins (R)	Optimized propeller blade section (R)
	Propulsion upgrade II	Counter-rotating propellers (N)	Wing thrusters (N)	Pulling thrusters (N)	
	Main engine adjustments	Common rail (R)	Diesel electric drive (N)	Diesel-electric drive and diesel-mechanical drive (N)	Main Engine Tuning (R)
	Waste heat recovery (R)				
	Wind power	Towing kite (R)	Wind engines (R)		
	Hybrid auxiliary power generation (N)				
	Solar power (R)				
	Reducing onboard power demand (hotel services)	Low energy lighting (R)	Energy efficient HVAC (R)	Energy efficient appliances (R)	
	Speed control of pumps and fans (R)				
	Scrubber (R)				
	Fuel-efficient boilers (R)				
	Low loss power distribution (N)				
	Alternative fuels	LNG (R)	Bio fuel (R)		

Description of Measures

5.17 In this section the abatement measures are described briefly in the order shown in Table 5-1. A technical description is given, applicability to ship types and/or size categories and market maturity are indicated. If known, abatement potential and cost data are described. The corresponding data is listed per ship type and ship size category; these tables can be found in the appendix. The abatement potential is given in the percentage of CO_2 emission reduction on a per ship basis. Two types of costs are being differentiated, non-recurring and annual recurring costs. Non-recurring costs are the costs associated with purchasing and installing a measure. Annually recurring costs are annual operational costs associated with the measure.

5.18 For several measures, a payback time is specified. For these measures cost data has been derived from a Wärtsilä brochure (Wärtsilä, 2008). In this brochure, the reduction potential and the payback time of different measures are specified. The payback time varies from very short, which is less than a year, to very long, which is more than 15 years. Assuming that the price of bunker fuel that underlies these data is US$ 300/metric 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. In this case only non-recurring costs are specified.

5.19 Some measures may dependent on for example a supporting measure such as monitoring system or a management program or service. These supporting measures are described, and the costs of these systems, programs or services are included in the costs of the primary measure. Several earlier published studies treated these separately.

Operational abatement measures

5.20 Operational abatement measures are measures that do not require physical changes to the ship. As shown in table 1, we have identified 8 groups of operational measures:

.1 Operational speed reduction

.2 Optimization of ballast and trim

.3 Efficiency of scale

.4 Weather routing

.5 Autopilot adjustment

.6 Increasing energy awareness

.7 Propeller maintenance

.8 Hull cleaning

5.21 Each of these measure groups is described in detail below.

Operational speed reduction

Speed reduction

5.22 By operating at lower speeds, ships reduce their power requirement and hence their fuel consumption. As a rule of thumb, power requirement is related to ship speed by a third power function. This means that a 10% reduction in speed results in an approximate 27% reduction in shaft power requirements. However, a ship sailing 10% slower would use approximately 11% more time to cover a certain distance. If this is taken into account, a new rule of thumb can be drafted stating that per tonne mile, there is a quadratic relation between speed and fuel consumption, so that a 10% decrease in speed would result in a 19% reduction in engine power.

5.23 Between engine loads of 100% maximum continuous rating (MCR) and 50% MCR, the fuel consumption is approximately linearly correlated with shaft power (in other words, the specific fuel consumption is constant within a range of ±3%. At 25% MCR the specific fuel consumption increases to about 10% above optimum specific fuel consumption for a 2-stroke main engine. In other words, the engine uses 10% more fuel per unit of power. Below 25% MCR, only few consumption data are available with increases between 40 and 100% compared to optimum. So at these loads, the rule of thumb cannot be applied.

5.24 Using these data, we arrive at the following relation between ship speed, engine load and fuel consumption:

Table 5-2: Relationship of speed, engine power and fuel consumption

Speed (% of design speed)	Engine power (% of MCR)	Fuel consumption
100%	75%	100%
90%	55%	73%
80%	38%	52%
70%	26%	35%

5.25 The potential to reduce speed is limited. Engines cannot be operated at any load without adjustments to the engine. The minimum load depends on the technical specification of the manufacturer for each individual engine. From a technical point of view, a ship operating on slow steaming is most probably operating in so-called "off-design conditions." Sailing in off design conditions may in some circumstances cause engine damage. Electronically controlled engines are more flexible to operate in off-design and can generally be operated at lower loads than mechanically controlled engines.

5.26 Applicability**:** Subject to the constraints with regards to sailing in off-design conditions, slow steaming can be applied by all ship types and size categories. Ships that have to maintain a route/time schedule, for example cruise vessels and ferries, will probably not make use of this measure.

5.27 Technical maturity**:** Slow steaming is currently being implemented by many shipping companies facing high fuel costs and low transport demand. It can thus be considered a technically mature option.

5.28 Abatement potential: see Appendix II. As described above, the relation between speed and emissions is given by a third power function, and, per tonne mile, by a quadratic function. The latter is specified in the two tables in the appendix, in one table for a speed reduction of 10% and in the other for a speed reduction of 20%. However, since reducing speed also means reducing transport work per unit of time, more ships are needed in order to perform the same transport work. Since these ships also consume fuel, the actual abatement potential is the square of the speed reduction in first approximation. We apply a second approximation, accounting for the fact that ships only spend a fraction of their time sailing at their design speed. Assuming that ships are reducing their speed at sea, but that the time in ports per call remains constant, the fleet needs to be increased by the following factor in order to deliver the same amount of transport work:

$$\boxed{F_1 = F_0 \left(\frac{\frac{DAS}{1-\Delta s} + (365 - DAS)}{365} \right)} \qquad (7)$$

Where:

F_0 – the number of vessels of ship type and size category in the fleet
DAS – days at sea per year for ship type and size category
Δs – speed reduction as % of design speed

5.29 Costs: see Appendix II. As described above extra capacity has to be used when ships are slow steaming and the same transport work has to be done. It is being assumed that this extra capacity is provided by new vessels. The non-recurring costs of the measure "speed reduction" are thus the costs for purchasing extra new vessels. The prices of the new-builds have been deduced from UNCTAD (UNCTAD, 2009). Since prices for new-builds have been very volatile, with 2007 being a year with above-average prices, we applied a correction factor of 0.7 to the 2007 data. The non-recurring costs given in the appendix are the costs for *one* new ship and are therefore the same for a speed reduction of 10% and of 20%. The annual recurring costs are the operational costs of the extra vessels.

Voyage optimization including reduced port time

5.30 Usually, the ship operator and the charterer stipulate a certain speed in the charter party. In case of port congestion, this contracted speed is not the optimal speed when it comes to fuel consumption; the ship could have been unloaded at the very same time but could have saved fuel by reducing its speed at sea. Concepts like the virtual arrival try to tackle this common problem. Here the ship operator and the charterer agree on a specific speed reduction against the contracted speed for the case that the ship is to be delayed on arrival due to port congestion or the like. To reduce the ships' time in port is another possibility of creating space for speed reduction.

5.31 Abatement potential: Based on prior analysis of demurrage rates by Navigistics Consulting 0-10%.

Applicability: Primarily for dry and liquid bulk vessels on spot charter.

5.32 Costs: not known. Making use of a virtual arrival system incurs the costs for a third party that is needed to calculate the revised estimated time of arrival (Portworld, 2009). Costs for reducing the time in port are associated with the costs for a more efficient port infrastructure (which may be passed onto the charterers by means of harbor fees) and/or with the costs for more efficient onboard loading devices.

Bulbous bow

5.33 A horizontal extension of the bow, just below the water surface, can reduce the drag of the bow wave with respect to the hull (Trudeau *et al*, 2009).

5.34 Applicability: Primarily for vessels with higher speed to length ratios. (e.g., container and cruise ships).

5.35 Technical maturity**:** available on the market.

5.36 Abatement potential**:** at least 10% (Bray, 2008); though most ships already have bulbous bows. Abatement potential is further limited to improved bulbous bow designs. A bulbous bow is only leading to a reduction of fuel consumption when the ship is operated at its design speed; therefore temporary speed reduction reduces the efficiency improvements of a bulbous bow. If a ships speed is permanently reduced, a new bow should be installed to recapture the efficiency gains.

5.37 Costs**:** There are investments associated with a bulbous bow. We do not have an estimate of these costs.

Optimization of trim and ballast

5.38 The trim that is optimal for a vessel under the different conditions can be detected by means of monitoring. Trim can be improved by arranging bunkers, by positioning cargo or by varying the amount of ballast water. Taking extra ballast water thereby leads to an increased displacement and therefore to an increased fuel consumption.

5.39 Abatement potential**:** <5%. (Wärtsilä, 2008)

5.40 Payback time**:** short. (Wärtsilä, 2008)

5.41 Costs: optimization of trim and ballast requires a vessel performance monitoring system. Investments are associated with buying or developing such a system. Operational costs are associated with collecting and analyzing data and with changing trim and ballast. The costs are not known.

Economies of Scale

Using larger existing ships

5.42 Since fuel consumption per tonne mile is in general higher for smaller than for larger ships, fuel savings can be gained by using larger instead of smaller ships as long a there is sufficient demand for transport. The use of larger ships may be constrained by port, canal and lock dimensions. Over the last decades, the average vessel size has increased considerably, especially in container ships. It is expected that this trend will continue.

5.43 Applicability: all cargo/passenger transport related ship types. However, cargo lot sizes are determined by the commodity buyer/seller and may not exactly match ship capacity.

5.44 Abatement potential: < 4%. (Wärtsilä, 2008)

5.45 Payback time: larger ships have lower operational costs. At the margin, the payback time is short. (Wärtsilä, 2008)

5.46 Costs: if the average size of ships increases, the capital costs per ship increase, but unit transport cost decrease. We have not quantified these costs.

Increasing cargo load factor

5.47 Ships often do operate without fully making use of their cargo loading capacity. If the load factor of ships was increased, the emissions of these ships would increase due to the increased weight of the vessel, however, this increase would be outweighed by the emissions saving of using a smaller number of ships. The uptake of this measure is limited by the fact that the cargo load factor is often set by transport demand. Increasing it may require changes in logistics.

5.48 Abatement potential: not known.

5.49 Costs: In principle, higher load factors have negative costs, although there may be positive costs associated with logistical services and optimization.

Weather routing

5.50 There are weather routing services available that help to optimize the route a ship takes, given the corresponding weather conditions. Reduction of travel time leads to a reduction of fuel consumption.

5.51 Applicability: ocean-going vessels that have route flexibility.

5.52 Abatement potential: 0.1-4% (Buhaug *et al,* 2009).However, a significant portion of the world's fleet already employs this technology. Therefore, the actual abatement potential is much lower.

5.53 Costs: US $800 – UW $1,600 p.a. (Buhaug *et al,* 2009) Costs are the same for all vessel types.

Autopilot adjustment

5.54 Adjusting the autopilot to the route and the operation area prevents unnecessary use of the rudder for keeping the ship on course.

5.55 Abatement potential: 0.5 – 3%. (Buhaug *et al*, 2009). However, a significant portion of the world's fleet already employs this technology. Therefore, the actual abatement potential is much lower.

5.56 Payback time: short. (Wärtsilä, 2008)

5.57 Costs: see Appendix II.

Increasing energy awareness

5.58 Increasing the energy awareness of the crew by means of training can lead to a change of behaviours that have an impact on the fuel consumption of ships. Energy awareness means turning off lights, optimising HVAC, et cetera.

5.59 Abatement potential**:** not known.

5.60 Costs: There are costs associated with training the crew. All operational costs are negative. Evidence suggests that the payback time is generally short.

Propeller maintenance

Propeller polishing

5.61 Propeller surfaces can be cleaned to reduce roughness and the accumulation of organic materials. This can be done on a regular basis or when monitoring of the propeller performance gives an indication to do so. Propeller polishing has widely been used over the last 5 years. It is estimated that half of the maximum abatement potential has already been captured. Estimates are based on industry interviews.

Polishing on a regular basis

5.62 Abatement potential**:** 2-5%. (Buhaug *et al*, 2009)

5.63 Costs**:** $3000 - $ 5000 per polishing for a single screw vessel; a quantity discount may be provided.

Polishing when required (including monitoring)

5.64 Abatement potential: 2.5 - 8 %.

5.65 Costs**:** see Appendix II. We have assumed that on top of the polishing that is being done on a regular basis, propeller monitoring is used and, if necessary, extra polishing is done.

Hull cleaning

5.66 By reducing the frictional resistance of a hull, consumption of bunker fuel and thus emissions of CO_2 can be reduced; this is the often the outcome of a hull resistance management program. One way of reducing the frictional resistance is to enhance the smoothness of a hull by means of coatings that prevent/reduce fouling (see above). In addition, the hull can be cleaned periodically. This is considered here.

5.67 Abatement potential**:** 1-10%. (Buhaug, *et al*, 2009). However, a significant portion of the world's fleet already employs this measuere. Therefore, the actual abatement potential is much lower.

5.68 Costs**:** see Appendix II; cleaning the entire hull costs $35 - $45 per foot of the ship based on the length overall (LOA). This is based on interviews with hull-cleaning companies.

Technical abatement measures

5.69 As shown below identified 20 groups of technological measures:

1. Lightweight construction
2. Optimisation hull dimension
3. Economies of scale
4. Hull coating
5. Optimization hull openings
6. Design speed reduction
7. Optimization propeller hull interface
8. Air lubrication
9. Propulsion upgrade I
10. Propulsion upgrade II
11. Main engine adjustments
12. Waste heat recovery
13. Wind power
14. Hybrid auxiliary power generation
15. Solar power
16. Reducing onboard power demand
17. Speed control of pumps and fans
18. Scrubber
19. Fuel-efficient boilers
20. Alternative fuels

5.70 Each of these measure groups is described in detail below.

Lightweight construction

5.71 A ship's weight can be reduced using lightweight structures. Steel can be replaced by lighter weight alternatives in non-structural elements or by lower weight high-tensile steel. At present, lightweight materials such as aluminium, carbon fibre or glass-fibre sandwich constructions are mainly used on planning high-speed craft. (Buhaug *et al.*, 2009) it is anticipated that the new common structural rules will facilitate the use of lightweight materials (e.g., increased use of high tensile steel).

5.72 Applicability**:** all ship types.

5.73 Technical maturity**:** In many cases high tensile steel is already used to some extent (IMO 2009).

5.74 Abatement potential**:** <7%. (Wärtsilä 2008) – Actual potential probably on the order of 0.1 -2%

5.75 Payback time: very short. (Wärtsilä, 2008)

5.76 Costs: Most lightweight materials are more expensive than steel. Moreover, there are costs associated with building with lightweight materials, as most shipyards are not used to them. The incremental new-building costs of lightweight ships are not known.

Optimization of hull dimensions

Optimum hull dimension

5.77 The main hull dimensions are determined at the design stage of the ship. They should meet the specific requirements of the ship such as the shipping routes, the type of ship, the deadweight tonnage and the ship speed. Optimizing the length and hull fullness ratio is important to reduce ship resistance. When the length is increased too large, it increases the wetted surface and frictional resistance. When the ratio is too small, the hull lines are too blunt and the resistance is increased too.

5.78 Applicability**:** all ship types.

5.79 Technical maturity**:** available on the market.

5.80 Abatement potential**:** A 5%-20% fuel reduction is feasible for the optimisation of the behaviour of the hull in still water. However performance in waves will differ significantly between ships. (Buhaug *et al*, 2009). For an "optimal main dimension" (Wärtsilä, 2008) gives a reduction potential on ship basis of 9% at most. However, operation at non-design speed will likely eliminate the abatement impact.

5.81 Costs**:** optimising hull dimensions requires investing in design of a ship, possibly including tank trials et cetera. In addition, costs may be associated with building the optimised ships we have not quantified these costs.

Aft waterline extension

5.82 The tapered aft of the vessel at the waterlines can be extended to reduce flow turbulence, resulting in only a small amount of propulsion from the watercraft being required to load onto the docking system.

5.83 Applicability**:** Container, RoRo, Ferries.

5.84 Technical maturity**:** available on the market.

5.85 Abatement potential**:** < 7%. (Wärtsilä 2008) Actual abatement potential is probably on the order of 0.1-2%.

5.86 Payback time**:** very short. (Wärtsilä, 2008)

5.87 Costs**:** not known.

Economies of scale

5.88 Since fuel consumption per tonne mile is in general higher for smaller than for larger ships, fuel savings can be gained by using larger instead of smaller ships as long a there is sufficient demand for transport. The use of larger ships may be constrained by port, canal, lock, and dock dimensions. Over the last decades, the average vessel size has increased considerably, especially in container ships. It is expected that this trend will continue.

5.89 Applicability: all cargo/passenger transport related ship types.

5.90 Technical maturity: available in the market.

5.91 Abatement potential: not known.

5.92 Costs: if the average size of ships increases, the capital costs per ship increase, but unit transport cost decrease. We have not quantified these costs.

Hull coating

5.93 By reducing the frictional resistance of a hull, consumption of bunker fuel 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. Costs and abatement potential of two different coatings, in the following referred to as 'Hull coating 1' and 'Hull coating 2', have been estimated in comparison to a regular TBT-free coating. Due to the lack of data the results have to be considered as rough estimations rather than precise calculations.

5.94 Applicability: all ship types.

5.95 Technical maturity: available on the market.

5.96 Abatement potential: see the appendix. Starting point of the estimation of the incremental benefits, in comparison is 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. We assume that these benefits differ between the different ship types. Moreover, we have received information from trials suggesting that the surface smoothness deteriorates quickly, thus reducing the fuel savings. 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.

5.97 Costs: see the appendix. Starting point of the estimation of the incremental costs of the coatings 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. 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 derived, making the simplifying assumption that the hull surface to be painted is proportional to the 2/3-power of the gross tonnage of the ship and that the incremental costs vary linearly with this estimated surface. 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.

Optimization of hull openings

Low-profile hull openings

5.98 Hull openings, such as openings for bow thrusters, can be designed and completed such that flow disturbances are minimized.

5.99 Applicability: all ship types.

5.100 Technical maturity: available on the market.

5.101 Abatement potential: not known.

5.102 Costs: Investments are needed in new designs of hull openings and their manufacture. We have no estimates of these costs.

Optimization water flow of hull openings

5.103 The water flow disturbances from hull openings can be reduced by installing scallops or grids.

5.104 Applicability**:** all ship types.

5.105 Technical maturity: available on the market.

5.106 Abatement potential: 1- 5%.

5.107 Payback time: very short. (Wärtsilä, 2008)

5.108 Costs: see Appendix II.

Covering hull openings

5.109 In order to reduce fuel losses some ship owners have welded plates over the ship's bow-thruster hull openings. Thrusters placed in these openings are then no longer usable, but tug-boats can be used instead.

5.110 Applicability: all ship types with bow thrusters.

5.111 Technical maturity: available on the market.

5.112 Abatement potential: Not known.

5.113 Costs: not known. The cost of enclosing a bow thruster opening can be estimated to be a rather low, however, the extra costs for the use of tug-boats has to be taken into account.

Design speed reduction

5.114 As described above, an emission savings can be reaped when a vessel is slow steamed. However, the specific fuel oil consumption will decline when a ship is no longer operated at its design speed. The design speed can be reduced by, on the one hand, *de-rating the main engine* or, on the other hand, by *using less powerful engines or engines that can deactivate cylinders* (so as to have available reserve power for safety considerations)*(*. Ships designed to steam at lower speeds will typically have different hull forms. In general, at lower speeds, hulls can be broader, thus increasing cargo capacity.

5.115 Applicability: all ship types.

5.116 Technical maturity: available in the market.

5.117 Abatement potential: higher than the abatement potential for speed reduction alone.

5.118 Costs: The new-building costs would probably be lower as the engine would be smaller and the ship would require less steel. Operational costs would also be lower, mainly due to fuel savings. However, a slower ship will have lower earnings as it is not able to perform as much transport work per unit of time as a faster ship. We have not quantified these costs.

Optimization propeller hull interface

Optimal propeller hull interaction

5.119 Redesigning hull, appendages and propeller can improve the interaction between these three elements.

5.120 Applicability: all ship types.

5.121 Technical maturity: available on the market.

5.122 Abatement potential: <4%. (Wärtsilä, 2008)

5.123 Payback time: very short. (Wärtsilä, 2008)

5.124 Costs: a redesign requires an investment. We do not have an estimate of these costs.

Optimization of skeg shape

5.125 A skeg is a sternward extension of the keel of ships that have a rudder mounted on the centre line. Designing the skeg properly can improve the water flow to the propeller disk.

5.126 Applicability: all ship types.

5.127 Technical maturity: available on the market.

5.128 Abatement potential: < 2% (Wärtsilä, 2008)

5.129 Payback time: very short. (Wärtsilä, 2008)

5.130 Costs: We do not have an estimate of these costs.

Interceptor trim plates

5.131 An interceptor trim plate is attached vertically to the transom of a vessel and can be lowered vertically, intercepting the water flowing under the hull, generating lift at the stern. This lift can be used to alter the longitudinal trim of the vessel, allowing it to be optimised for the speed and the sea conditions. (Nautica, 2003)

5.132 Applicability: Can be used with any type of propulsion; RoRo, Ferry, Cruise

5.133 Technical maturity: many more cruise ships and ferries were tested with an Interceptor (Marin, 2005);

5.134 Abatement potential: < 4% (Wärtsilä, 2008)

5.135 Payback time: very short. (Wärtsilä, 2008)

5.136 Costs: interceptor trim plates require an investment. We do not have an estimate of these costs.

Air lubrication

5.137 Frictional resistance of a vessel's hull surface can be reduced by a so called air cavity system. Such a system has to be integrated into the flat bottom part of a vessel. An air injection system delivers air to the cavity through a system of automated compressors and valves. A control system monitors the volume and pressure of the air and maintains the optimal air level in the air cavity. Specifications below are with respect to the original system that was specifically designed for new vessels. A retrofit version is under development.

5.138 Applicability: The original system can only be applied to new-builds with a minimum length of 225 metres (LOA) and with, a least partly, flat bottom. A technical concern for deep draft vessels compressors may have problems maintaining air cavities.

We therefore decided to consider the following vessels as potential users:

1. − Crude oil tanker and bulk carriers > 60,000 dwt.
2. − LPG tankers with 50,000 m3 capacity and more.
3. − All LNG tankers.
4. − Full container vessels > 2000 TEU.

5.139 Technical maturity: Next to tank test, sea trials have been conducted with a small demonstration vessel. The technology is available on the market.

5.140 Abatement potential: 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. 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.

5.141 Costs: see Appendix II. The incremental non-recurring costs are expected to be 2-3% of the price of a conventional newly buil vessel (without ACS). We deduced the prices for new-builds from UNCTAD (2008), applying a correction factor of 0.7, since prices were exceptionally high in 2007. Operational costs of the system translate into 0.3 to 0.5 tons of fuel per day, depending on sea conditions. These operational costs thus depend on the fuel price and are therefore not specified in the table in the annex. Operational costs for maintenance may rise due to the application of an ACS. These extra costs are not taken into account.

5.142 Learning Rate: A 10% cost reduction is applied to represent the cost reduction as the technology is widely used.

Propulsion upgrade I

Propeller-rudder upgrade (change of rudder profile and propeller)

5.143 An integrated propeller rudder design with a rudder bulb can reduce the drag of the rudder.

5.144 Applicability: tanker, container, RoRo.

5.145 Technical maturity: available on the market.

5.146 Abatement Potential: 2- 6 %. (Buhaug *et al*, 2009)

5.147 Payback time: medium (Wärtsilä, 2008)

5.148 Costs: see Appendix II.

Propeller upgrade (nozzle, tip winglets etc.)

5.149 Energy losses can occur at the tip of the propeller blades from water escaping from the high pressure side to the low pressure side. Both, a nozzle, i.e. a ring around the propeller, and winglets at the tip can reduce these energy losses.

5.150 Applicability: tankers.

5.151 Technical maturity: available on the market.

5.152 Abatement Potential: 0.5 – 3%. (Buhaug *et* al, 2009)

5.153 Payback time: medium. (Wärtsilä, 2008)

5.154 Costs: see Appendix II.

Propeller boss cap with fins

5.155 Using a propeller boss cap with fins, the hub vortex is eliminated and energy can be recovered from the rotation flow around the boss. (Ouchi *et al*, 1990)

5.156 Applicability: all ship types.

5.157 Technical maturity: available on the market.

5.158 Abatement potential: tanker operators reported a reduction of 1-3%; for higher speed vessels, reduction may be higher.

5.159 Costs: see Appendix II. Capital costs are according to Frey *et al* (2007) US$ 20,000 for a 735 kW engine and US$146,000 for a 22,050 kW engine. Taking this data as starting point we estimated the capital costs for the different ship types, simplifying assuming that there is a linear relationship between the power of the main engine and the price for the boss cap. Operational costs are not known (Frey *et al*, 2007)

Optimized propeller blade section

5.160 Propeller efficiency can be enhanced by optimizing the propeller blade section, improving cavitation and frictional resistance of a blade.

5.161 Applicability: all ship types.

5.162 Technical maturity: available in the market.

5.163 Abatement potential: <2%.(Wärtsilä, 2008)

5.164 Payback time: very short. (Wärtsilä, 2008)

5.165 Costs: 10-15% Higher propeller costs based on interview with manufacturers.

Propulsion upgrade II

Contra-rotating propellers

5.166 In a contra-rotating configuration two propellers are facing each other, rotating in the opposite direction, with the aft propeller recovering the rotational energy in the slipstream from the forward propeller.

5.167 Applicability: 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 (Buhaug *et al,* 2009), as for example very fast RoRo ferries or ice breakers.

5.168 Technical maturity: available on the market; problems with gearboxes for contra-rotating propellers have been reported (Buhaug *et al,* 2009), as well as operational problems with bearings.

5.169 Abatement potential: Reported gains in power consumption range from 6% to 20%. Gains of 15% and 16% have been reported from two different full-scale measurements. Analysing the losses of rotational energy suggests that the potential gains that could be obtained are around 3-6%. (Buhaug *et al,* 2009)

5.170 Costs: counter-rotating propellers require an investment. We do not have an estimate of the associated costs.

Wing thrusters

5.171 A wing-thruster configuration is a configuration with a mechanical centre line propeller and two azimuthing propulsors on each side. This configuration makes the vessel good to manoeuvre and makes thrusters in the stern obsolete. For high power applications is the split of the load between three propellers beneficial.

5.172 Applicability: RoRo, Ferry (not: tankers, containers)

5.173 Technical maturity: available on the market.

5.174 Abatement potential: <10%. (Wärtsilä, 2008)

5.175 Payback time: medium. (Wärtsilä, 2008)

5.176 Costs: wing thrusters require an investment. We do not have an estimate of the associated costs.

Pulling thrusters

5.177 A pulling propeller is oriented towards and not against the direction of travel. The usage of steerable thrusters with a pulling propeller leads to power savings.

5.178 Applicability: RoRo and ferries.

5.179 Technical maturity: available on the market.

5.180 Abatement potential: <10%. (Wärtsilä, 2008)

5.181 Payback time: medium. (Wärtsilä, 2008)

5.182 Costs: pulling thrusters require an investment. We do not have an estimate of the associated costs.

Main engine adjustments

Common Rail Technology

5.183 With the common rail technology combustion of diesel-mechanical engines is optimized over the different operating fields.

5.184 Applicability: all ship types using diesel-mechanical engines.

5.185 Technical maturity: available on the market.

5.186 Abatement potential: 0.1 - 0.5%. (Buhaug *et al,* 2009)

5.187 Payback time: short. (Wärtsilä, 2008)

5.188 Costs: see Appendix II.

Diesel electric drive (and diesel-mechanical drive)

5.189 The fuel efficiency loss at lower speed can also be reduced by making use of a diesel-electric propulsion system instead of a diesel-mechanical propulsion system (or by a combination of both). In case of diesel-mechanical propulsion systems a diesel engine is driving the main propeller shaft and the onboard power demand is met using a separate diesel generator. When diesel-electric propulsion is used an electrical motor is driving the main propeller whose demand is met by a larger electrical power plant.

Diesel-electric propulsion

5.190 Applicability: RoRo, Ferry, Cruise

5.191 Technical maturity: available on the market.

5.192 Abatement potential: < 20% (Wärtsilä, 2008), depending on operational profile; electric propulsion introduces additional transmission losses that may offset the gains; the higher flexibility with which the below-deck space can be used may translate into energy savings (Buhaug *et al*, 2009).

5.193 Payback time: medium. (Wärtsilä, 2008)

5.194 Costs: not known.

Diesel-electric propulsion and diesel-mechanical drive

5.195 Applicability: RoRo, Ferry, Cruise

5.196 Technical maturity: available on the market.

5.197 Abatement potential: not known.

5.198 Costs: not known.

Main Engine Tuning

5.199 In main engine turning, the most commonly used load ranges have to be determined and then the main engine is optimized for operation at that load. This measure requires a different engine mapping and entails changes in cam profiles and injection timing. This measure can reduce overall fuel although there may be a fuel use penalty under seldom-used full load operations.

5.200 Applicability: All types of ships except ferry and cruise

5.201 Technical maturity: available on the market.

5.202 Abatement potential: 0.1 - 0.8%. (Buhaug *et al,* 2009)

5.203 Payback time: short. (Wärtsilä, 2008)

5.204 Costs: see Appendix II.

Waste heat recovery

5.205 With a waste heat recovery (WHR) system the waste heat of the engines can be used to drive turbines for electricity production, leading to less fuel consumption by the auxiliary engines.

5.206 Applicability: A WHR system is reasonably applied to ships with a high production of waste heat and a high consumption of electricity. Therefore we have assumed that only those ship owners who would employ WHR have main engines' with average performance higher than 20,000 kW and with auxiliary engines' with average performance higher than 1,000 kW.

5.207 Technical maturity: available on the market.

5.208 Abatement potential: see Appendix II. As to the emission reduction potential, different numbers can be found in the literature. For higher output engines Wärtsilä assesses a high efficiency WHR plant to be able to recover up to about 12% of the engine shaft power. In the case study given in the same leaflet the saving amounts to 11.3 %. On the other hand, the upper percentage of the potential annual saving in fuel costs is given to be lower than 10% (Wärtsilä 2008).Siemens (2009) estimates the saving of energy costs of a combination of an electrical booster drive and WHR to be approximately 12%. Given these figures we decided to assume an emission reduction potential of 8-10%(Siemens 2009). When the efficiency of an engine is improved or speed is reduced, less waste heat is being discharged, leading to lower abatement potential.

5.209 Costs: see Appendix II.

5.210 Learning Rate: A 10% learning rate is applied to the waste heat recovery technology. It is assumed that as this technology is mature, cost will be reduced by 15%.

Wind power

Towing kite

5.211 With a kite that is attached to the bow of a ship wind energy can be used to substitute power of the ship engines.

5.212 Applicability: 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. The system can be retrofitted.

5.213 Technical maturity: Until now, kites that have an area of up to 640 m2 for cargo vessels, fishing trawlers and yachts are available. By now, kite systems have been installed to a small number of commercial ships (multipurpose cargo vessel and fishing trawler). All 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 of a towing kite, we assume that in 2030 kites up to 5,000 m^2 are available in the market.

5.214 Abatement potential: see Appendix II. It is difficult to determine the potential reduction of fuel consumption 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 the following table, the engine equivalent powers we used for the different kite sizes are given. These numbers hold under standard conditions.[15]

Table 5-3: Approximate engine equivalent power used for the different kites

Kite area (m^2)	Engine equivalent power (kW)
160	600
320	1200
640	2500
1280	4900
2500	9600
5000	19200

For the lower (higher) bound estimate we assume that the kite can be used 1/3 (2/3) of the days at sea.

5.215 Costs: see Appendix II. The cost data that were used are given in the following table. 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 the installation costs of retrofit and non-retrofit systems. Note that the cost data are such that possible reinvestments during the lifetime of a vessel, i.e. 30 years, are included.

Table 5-4: Cost estimates for a towing kite system

	Kite area (m^2)				
	320	640	1280	2500	5000
Purchase price (thousand US$)	480	920	1,755	2,590	3,430
Installation costs (% of purchase price)	7.5%	7.5%	7.5%	7,5%	7,5%
Operational costs per annum (% of purchase price)	5-7%	7-9%	9-11%	11-13%	13-15%

15 The standard conditions are defined as follows: the vessel cruises at a speed of 10 knots at a true wind course of 130º, the wind speed is 25 knots, waves are up to 60 cm high and the kite is manoeuvred dynamically.

Wind engines

5.216 Rotors placed on deck of a ship can generate thrust, taking advantage of the so-called Magnus effect.

5.217 Applicability: Greenwave estimates that vessels upwards of 10,000 dwt of the following types could be 'most immediately' applicable for wind energy technology from the 'available footprint'[16] point of view: crude oil tankers, chemical tankers, product tankers, and bulk carriers. A four wind engine system (two forward and two aft) is preferable for bulk carriers as the wind engines must be out of the way of cargo operations and the hatch covers over cargo holds. A three engine system with a center-line configuration may be applied to tankers where crane operations are involved. We therefore assume that a four engine system is applied to bulkers and a three engine system to tankers. Since data is only available for a Supramax bulker with 55,000 dwt we only takeinto account, for the sake of comparability, only tankers and bulkers with more than 60,000 dwt as potential user of wind engines (Greenwave, 2009).

5.218 Technical maturity: Greenwave carried out scale model tests. Enercon has ordered a cargo ship (E-ship 1) equipped with four wind engines which is expected to be finished in summer 2010 (Greenwave 2009).

5.219 Abatement potential: see Appendix II. For a Supramax bulker with 55,000 dwt equipped with a four wind engine system (rotor height 20 m and rotor diameter 2.3 m) that is 246 days at sea per annum Greenwave estimates an average fuel consumption saving of 1,023 tons per year. We assumed that the reduction potential for the different ship types was in absolute terms per rotor and per day the same as the one featured by the Supramax bulker; large wind engines would augment the air resistance of a ship (Greenwave, 2009).

5.220 Costs: see Appendix II. Greenwave estimates that the costs for manufacturing and installing of four wind engines lies in the range of US$ 0.8 m – US$ 1 m.(Greenwave, 2009). We assumed that the costs for manufacturing and installing rotors are linear in the number of wind engines. The operational costs are not known.

5.221 Learning rate: Both the wind engine and kite are new technologies and may be subject to cost reduction when the technology is widely applied to ships. Therefore, the 15% learning rate is applied to capture the technology progress. This rate is based on the learning curves of onshore and offshore wind power analyses.

Hybrid auxiliary power generation

A hybrid auxiliary power system consists of a fuel cell, diesel generating sets and batteries.

5.222 Applicability: all ship types.

5.223 Abatement potential:< 2% (Wärtsilä, 2008)

5.224 Payback time: very short. (Wärtsilä, 2008)

5.225 Costs: We do not have an estimate of the associated costs.

[16] Footprint means the area that is required on deck for the installation of a rotor.

Solar power

5.226 Solar energy can be used to deliver electricity for the onboard power demand.

5.227 Applicability: Solar cells can only be placed on ships that have sufficient deck space available. Therefore it is assumed that they can be used by tankers, vehicle carriers, and RoRo vessels.

5.228 Technical maturity: Under development.

5.229 Abatement potential: see Appendix II. Since investment costs are only known from the installation of solar cells to a Japanese car carrier, we assume the abatement potential to the 40 kW that have been installed in this case. Replacing 40 kW of the auxiliary engines by solar cells, the abatement potential of the solar cells is within a range of 0.2 and 3.75%.

5.230 Costs: see Appendix II. For a car carrier that installed 40kW of solar cells the investment costs are known to be $1.67 million USD Yen. Due to a lack of further cost data we simplifying assume that if a ship makes use of solar energy it installs solar cells to the very same extent and at the very same costs. The cost of solar power may decrease in the future when the technology is mature and applied to large scales of ships. A 15% learning rate is applied to capture is effect. This learning rate is based on onshore solar power analysis (Van der Zwaan *et al*, 2003).

Reducing onboard power demand

5.231 There are many different ways to reduce the power demand onboard. Three of these options are considered here, i.e. the use of more electricity and heat efficient lighting, the use of energy efficient heating, ventilation and air condition, and the usage of pumps and fans at variable speed, according to the actual need.

Low energy lighting

5.232 Applicability: lighting is a relevant factor on ferries, RoPax and cruise vessels.

5.233 Technical maturity: available on the market.

5.234 Abatement potential: 0.1 - 0.8 %. (Buhaug *et al*, 2009)

5.235 Payback time: medium. (Wärtsilä, 2008)

5.236 Costs: see Appendix II.

Energy efficient Heating, Ventilation and Air conditioning (HVAC)

5.237 Applicability: all ship types.

5.238 Technical maturity: available on the market.

5.239 Abatement potential: not known.

5.240 Costs: not known.

Speed control of pumps and fans

5.241 Applicability: all ship types.

5.242 Technical maturity: available on the market.

5.243 Abatement potential: 0.2 – 1 % (Buhaug *et al*, 2009)

5.244 Payback time: medium. (Wärtsilä, 2008)

5.245 Costs: see Appendix II.

Scrubber

5.246 Ecospec has developed the CSNOx scrubber which is claimed to remove CO_2 and air pollutants from exhaust gas. (Ecospec, 2010)

5.247 Applicability: all ship types.

5.248 Technical maturity: Ecospec reports two trials. (Ecospec 2010). There is significant scepticism in the industry over these claims.

5.249 Abatement potential: Ecospec reports a removal rate of CO_2 from the exhaust gas of 74%-77% in two trials (Ecospec, 2010).

5.250 Costs: not known.

Fuel-efficient boiler

5.251 Auxiliary boilers on diesel driven ships are used for supplying steam and hot water for non-propulsion uses such as fuel heating, galley, cabin space heating, and to drive steam turbines on tankers that offload petroleum crude oil in port. (Miller et al., 2009)

5.252 Applicability: can be applied to all ships making use of boilers; lends itself the best to the application on crude oil and product tankers since boiler emissions carry most weight for these ship types.

5.253 Technical maturity: available on the market.

5.254 Abatement potential: not known.

5.255 Costs: not known.

Low-less power distribution

5.256 With a low less power distribution the number of (large) distribution transformers that is needed for a diesel-electric propulsion arrangement can be reduced. This leads to a reduction of distribution losses, saving of space and installation costs.

5.257 Applicability: RoRo, ferry, cruise.

5.258 Technical maturity: available on the market.

5.259 Abatement potential: < 2% (Wärtsilä, 2008)

5.260 Payback time: medium. (Wärtsilä, 2008)

5.261 Costs: not known.

Alternative fuels

5.262 CO_2 emissions can be reduced when alternative fuels are used instead of/in addition to diesel fuel. Liquefied natural gas (LNG) and bio fuels are alternative fuels that are associated with lower life-cycle CO_2 emissions. For instance the carbon emitted when burning bio fuels is offset by the carbon the plants absorb while growing. Making use of alternative fuels will also lead to a reduction of CO_2 emissions from less heating and separating of heavy fuel oil.

LNG

5.263 Applicability: In principle all ship types could make use of LNG. However, safety regulations can limit the use. It is for example not allowed to place tanks on the deck of a passenger ship (Hoogma *et al*, 2009).Usage may also be limited due to a lack of supply of LNG in harbours.

5.264 Technical maturity: ships transporting LNG often use LNG as fuel; little use is made of LNG by other ship types (Hoogma *et al*, 2009); technology is being developed further.

5.265 Abatement potential: Liquefied natural gas has a lower carbon to hydrogen ratio than diesel fuels. Increased emissions of methane however reduce the net effect to about 15% reduction in CO2 equivalent emissions (AEA, 2008).

5.266 Payback time: medium. (Wärtsilä, 2008)

5.267 Costs: Not known. The price of LNG is less compared to distillate fuels. In the past there have been periods when the LNG price was above or below the HFO price. Since LNG needs to be cooled and/or compressed, different fuel tanks and piping may be needed. In addition, because of the lower energy density of LNG, ships have to bunker more often or need bigger tanks.

Bio fuels

5.268 Applicability: all ship types.

5.269 Technical maturity: bio fuel is available on the market but not on a large scale.

5.230 Abatement potential: A 1998 biodiesel lifecycle study, jointly sponsored by the US Department of Energy and the US Department of Agriculture, concluded biodiesel reduced net CO_2 emissions by 78 % compared to petroleum diesel. Carbon emissions from extra land use (natural land stores carbon) should be taken into account here. The abatement potential of bio fuels varies widely, especially when impacts of induced land use change are taken into account

5.231 Costs: Ships can make use of biodiesel without having to undergo big technical changes (Wärtsilä, 2009); however, bio fuels are still rather expensive (Buhaug *et al*, 2009).

CHAPTER 6

ANALYSIS AND ESTIMATION OF CO_2 MARGINAL ABATEMENT COST CURVES

6.1 The cost-effectiveness or MAC of fuel saving measures was determined by the cost of fuel-saving measures, the fuel saving potentials, the fuel cost, the discount rate, the learning rate, and ship type, size, and age (see Chapter 3). The cost and fuel efficiency improvement potentials of individual measures are shown in Appendices II and III, respectively. This Chapter shows the other factors that influence the cost-effectiveness, explains the procedure of estimating the cost-effectiveness and the MAC curve (MACC) and demonstrates the results.

6.2 For each measure, the cost-effectiveness at the introducing year was first calculated, using the formula introduced in Chapter 3:

$$\boxed{MAC = \frac{\Delta C_j}{\alpha_j \times CF \times F} = \frac{K_j + S_j - E_j + \sum O_j}{\alpha_j \times CF \times F}}$$

6.3 Cost estimates and emissions reduction, by ship type, size and age are provided in Appendix II for the years 2020 and 2030. The fuel conservation for each ship was assumed to be unchanged in 2020 and 2030; what changed were the fuel price and the number of ships per category. After the computation of the cost-effectiveness of each measure for each ship category, energy-efficiency improvement measures within one group were compared and ranked. For each ship category, the measure with the best cost-effectiveness was selected for inclusion in the MACC.

6.4 In a second step, measures were rank ordered on the basis of their cost-effectiveness. The one with the best cost-effectiveness was assumed to be applied first, followed by the one with the second best cost-effectiveness, and so on.

6.5 The following is an example illustrating this approach. There are one of two measures, hull coating "1" and hull coating "2" that can be applied to reduce fuel consumption and examined in our analysis to calculate the cost-effectiveness of the measure. These coatings are mutually exclusive. The introducing year of both coating methods was 2007 and these measures are effective for five years. We assumed that the fuel prices of bunkers in 2020 and 2030 would be $700 per ton and $900 per ton, respectively. We also assumed that the discount rate is 10% and the lifetime of a ship is 30 years. Ships were divided into 318 categories by ship type, size, and age. We assumed that all ships, no matter how many years of expected service remain can employ this option. A more specific example that we studied was the application of hull coatings on a SuezMax crude tanker between 120,000 and 199,999 deadweight tonnage (dwt) in 2020.

1. The crude tankers that are 2.5 years old, 7.5 years old, 12 years old, 17 years old, 22 years old, and 27 years old accounted for 38.8%, 28.3%, 16.0%, 12.5%, 2.8%, and 1.5%, respectively of the current fleet of crude tankers.

2. In 2020, for the first three categories, they become 15 years old, 20 years old, and 25 years old. For the latter three categories, they become 0 years old, 5 years old, and 10 years old.

3. In other words, in 2020, we assumed that the very old ships would be retired and would be replaced by old ships with some remaining service life. In 2020, we assumed that the shares of each age group also change. For the first three age groups, the number of ships remained the same. But for latter three groups, we assumed that more new ships enter the market than ships that retire by 2020. The group rate was based on the future forecast by the IMO 2009 GHG report, which indicated that the crude tanker with the dwt between 120,000 and 199,999 dwt would increase by 1.21% by 2020 based on 2007 level.

6.6 Based on this baseline information, the fuel savings per individual ship was the combination of fuel saving potential times the yearly fuel consumption. The source of yearly fuel consumptions were from the IMO 2009 GHG report. The specific estimates of the fuel saving potential are provided in table 6-1 and Appendix II. The estimated CO_2 saving per ship per year was converted from fuel savings. This study assumed one ton of fuel produces 3.13 tonnes of CO_2 (Table 6-1). The total fuel and CO_2 savings of this type of crude tanker were then calculated by taking into account the total number of ships in each age category (Table 6-1 and Table 6-2). The total fuel saving was the fuel price ($700 per ton) times the tons of fuel saved.

Table 6-1: Fuel savings and CO_2 savings per ship for hull coating 1 in 2020

					Fuel savings (ton per ship per year)		CO2 savings (ton per ships per year)	
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate
01 Crude	Tanker	B	B 120 -199,999 dwt	15.0	132	546	412	1709
01 Crude	Tanker	B	B 120 -199,999 dwt	10.0	132	546	412	1709
01 Crude	Tanker	B	B 120 -199,999 dwt	5.0	132	546	412	1709
01 Crude	Tanker	B	B 120 -199,999 dwt	30.0	132	546	412	1709
01 Crude	Tanker	B	B 120 -199,999 dwt	25.0	132	546	412	1709
01 Crude	Tanker	B	B 120 -199,999 dwt	20.0	132	546	412	1709

Table 6-2: Fuel and CO_2 savings in tonnes and fuel savings in US$ for hull-coating 1 in 2020

					Fuel savings (ton per year)		CO2 savings (ton per year)		Fuel savings ($ per ship per year)		Fuel savings ($ per year)	
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate	Low Estimate	High Estimate	Low Estimate	High Estimate
01 Crude	Tanker	B	B 120 -199,999 dwt	15.0	18,070	74861	56559	234316	92,240.8	382,140	12,649,006	52,403,025
01 Crude	Tanker	B	B 120 -199,999 dwt	10.0	13,174	54576	41233	170824	92,240.8	382,140	9,221,534	38,203,496
01 Crude	Tanker	B	B 120 -199,999 dwt	5.0	7,461	30911	23353	96750	92,240.8	382,140	5,222,815	21,637,378
01 Crude	Tanker	B	B 120 -199,999 dwt	30.0	8,464	35067	26494	109760	92,240.8	382,140	5,925,140	24,547,008
01 Crude	Tanker	B	B 120 -199,999 dwt	25.0	3,918	16231	12263	50803	92,240.8	382,140	2,742,487	11,361,731
01 Crude	Tanker	B	B 120 -199,999 dwt	20.0	3,335	13816	10438	43245	92,240.8	382,140	2,334,454	9,671,310

6.7 For each measure four cost-effectiveness figures were then calculated; these were estimates of a high reduction potential and a low reduction potential. For each reduction potential, there was one high cost estimate and one low cost estimate. The high reduction

potential was associated with the high energy-efficiency improvement data and the low reduction potential was associated with the low energy-efficiency improvement data in provided in Chapter 5 Section Two. The high cost data were associated with the high cost of hull coatings and the low cost data were associated with the low cost of hull coatings, also provided in Chapter 5 Section Two. The high estimate of the low reduction potential and the low estimate of the high reduction potential were then picked as the lower bound and higher bound of the cost-effectiveness for the hull coatings in this study (Table 6-3). A full list of high and low cost estimates for high and low reduction potentials for hull coating 1 are presented in the Appendix III. To save space, the high and low costs for high and low reduction potentials of other measures are online at
http://www.sname.org/SNAME/climatechange/MACreport and
http://www.theicct.org/programs/Marine.

					MAC low reduction potential		MAC high reduction potential	
Category 1	**Category 2**	**Category 3 (big or small)**	**Category 4 (size)**	**Category 7 (ship remaining life time)**	**Low Estimate**	**High Estimate**	**Low Estimate**	**High Estimate**
01 Crude	Tanker	B	B 120 -199,999 dwt	15.0	-172.7	-117.9	-211.4	-198.1
01 Crude	Tanker	B	B 120 -199,999 dwt	10.0	-172.7	-117.9	-211.4	-198.1
01 Crude	Tanker	B	B 120 -199,999 dwt	5.0	-172.7	-117.9	-211.4	-198.1
01 Crude	Tanker	B	B 120 -199,999 dwt	30.0	-172.7	-117.9	-211.4	-198.1
01 Crude	Tanker	B	B 120 -199,999 dwt	25.0	-172.7	-117.9	-211.4	-198.1
01 Crude	Tanker	B	B 120 -199,999 dwt	20.0	-172.7	-117.9	-211.4	-198.1

Table 6-3: Cost-effectiveness for hull-coating 1 in 2020

6.8 The cost-effectiveness of coatings 1 and 2 are then compared because they are mutually exclusive. Ships that employ coating 1 would not employ coating 2 at the same time. The assumption was made that ship owners would choose the most cost-effective coating. For SuezMax tankers mentioned in this example, it was assumed that coating 1 would be selected because hull coating 1 has lower cost-effectiveness for all age groups (Table 6-4).

Table 6-4: Comparison of cost-effectiveness for hull coating 1 and 2

					Marginal Abatement Cost			
					Coating 1	Coating 2	Coating 1	Coating 2
Category 1	**Category 2**	**Category 3 (big or small)**	**Category 4 (size)**	**Category 7 (ship remaining life time)**	**Low Estimate**	**Low Estimate**	**High Estimate**	**High Estimate**
01 Crude	Tanker	B	B 120 -199,999 dwt	15.0	-117.9	-55.9	-211.4	-198.6
01 Crude	Tanker	B	B 120 -199,999 dwt	10.0	-117.9	-55.9	-211.4	-198.6
01 Crude	Tanker	B	B 120 -199,999 dwt	5.0	-117.9	-55.9	-211.4	-198.6
01 Crude	Tanker	B	B 120 -199,999 dwt	30.0	-117.9	-55.9	-211.4	-198.6
01 Crude	Tanker	B	B 120 -199,999 dwt	25.0	-117.9	-55.9	-211.4	-198.6
01 Crude	Tanker	B	B 120 -199,999 dwt	20.0	-117.9	-55.9	-211.4	-198.6

Table 6-5: Choosing the measure with lower cost-effectiveness between coating 1 and coating 2 in 2020

					Comparision							
					Selected measure	CO2 savings	CO2 savings	Measures	Selected measure	CO2 savings	CO2 savings	Measures
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate of MAC	Related CO2 savings	Related CO2 savings %	Related Measures	High Estimate of MAC	Related CO2 savings	Related CO2 savings %	Related Measures
01 Crude	Tanker	B	B 120 -199,999 dwt	15.0	-117.9	56559	0.7	Coating 1	-211.35	234316	2.9	Coating 1
01 Crude	Tanker	B	B 120 -199,999 dwt	10.0	-117.9	41233	0.7	Coating 1	-211.35	170824	2.9	Coating 1
01 Crude	Tanker	B	B 120 -199,999 dwt	5.0	-117.9	23353	0.7	Coating 1	-211.35	96750	2.9	Coating 1
01 Crude	Tanker	B	B 120 -199,999 dwt	30.0	-117.9	26494	0.7	Coating 1	-211.35	109760	2.9	Coating 1
01 Crude	Tanker	B	B 120 -199,999 dwt	25.0	-117.9	12263	0.7	Coating 1	-211.35	50803	2.9	Coating 1
01 Crude	Tanker	B	B 120 -199,999 dwt	20.0	-117.9	10438	0.7	Coating 1	-211.35	43245	2.9	Coating 1

6.9 The cost-effectiveness of coating (whenever it is coating 1 or coating 2) is then compared with another within any of the 14 groups of energy-saving measures. Again the option that has the lowest cost-effectiveness is chosen by ship type, size, and age first and then so on.

6.10 For illustration purpose, the calculation table is divided and only some parts are selected. For the cost-effectiveness of all ship type, size, and age combinations for hull coating 1, Appendix II provides an example. The whole calculation process as well as the cost-effectiveness for all 318 ship type, size, and age can be viewed on the websites of the ICCT and SNAME.

Total Cost Effectiveness or MAC Estimates

6.11 Table 6-6 provides the total estimated reduction potential in 2020 and 2030. The maximum abatement potential of the measures evaluated was estimated to be between 225 and 590 Mt of CO2 in 2020. The maximum abatement potential of the measures that were evaluated was estimated to be between 396 and 913 Mt of CO2 in 2030. These were about 20% to 46% reduction from the scenario of "business as usual" (BAU) in 2020 and 2030, using the sector growth rate projected in the IMO 2009 GHG report. The maximum reduction potential is larger than the estimate found in some of the previous literature in that ships use the energy-efficiency improvement saving technologies and operational measures almost regardless of the ship's age. Another reason is that compared with earlier studies, we considered more of the abatement measures are not mutually exclusive and that the prior conclusions were too conservative, leading to more measures that can be combined.

Table 6-6: Emission reduction in 2020 and 2030 (million metric tonnes)

	2020	2030
Low estimate	225	396
Central Estimate	436	677
High Estimate	590	913

6.12 Since both discount rate and bunker fuel prices play very important roles in determining the marginal costs of a certain measure, sensitivity analyses are performed with two alternative bunker fuel prices and discount rates. Alternative discount rates and fuel prices are used. The discount rates are 4.0% and 18% as low and high estimates, respectively. A higher discount rate results in higher annual non-recurring costs of the measures as well as costs due to lost service. This leads to higher marginal abatement costs. Because annual recurring cost is not influenced by the discount rate, the cost effectiveness of different measures was influenced in different degrees. The retrofitting measures were more influenced by the discount rate than the operational measures were. The cost effectiveness also varied as a function of ship size, with smaller ships generally having higher MAC. While not shown in this section, these differences are apparent when examining the tables in Appendix III and the data sets online http://www.theicct.org/programs/Marine and http://www.sname.org/SNAME/climatechange/MACreport.

6.13 Graphs based on the cost-effectiveness and CO_2 emissions reduction potential are depicted in the marginal abatement cost curve (MACC). The lower, higher, and central estimates are best illustrated graphically. There are also lower, higher, and central estimates without speed reduction as speed reduction has been realized to be a powerful measure to reduce CO_2 emissions. This study showed the differences with and without speed reduction in terms of cost and total CO_2 reduction in a quantitative manner. Figure 6-1 to Figure 6-4 show the aggregated MACC, including all ships (318 categories) for 2020 and 2030, respectively with and without speed reduction. In 2020 and 2030, the estimated reductions were about 20% to 46% emission reduction from the 2007 baseline level.

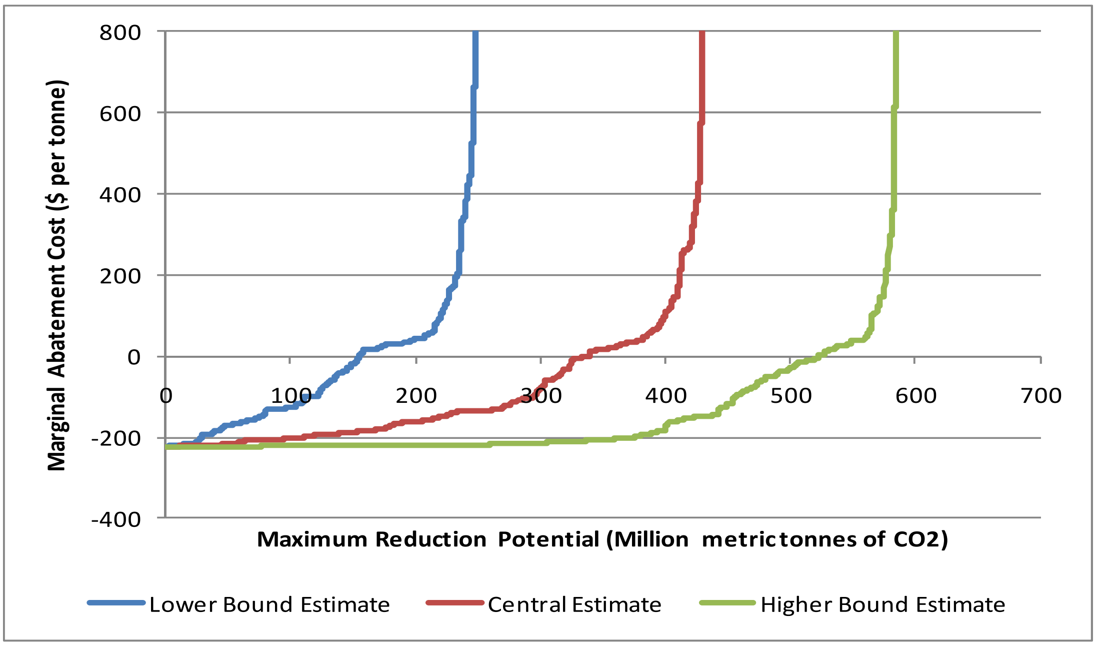

Figure 6-1: Aggregated MACC in 2020 with $700 per ton fuel price and 10% discount rate for all ship types.

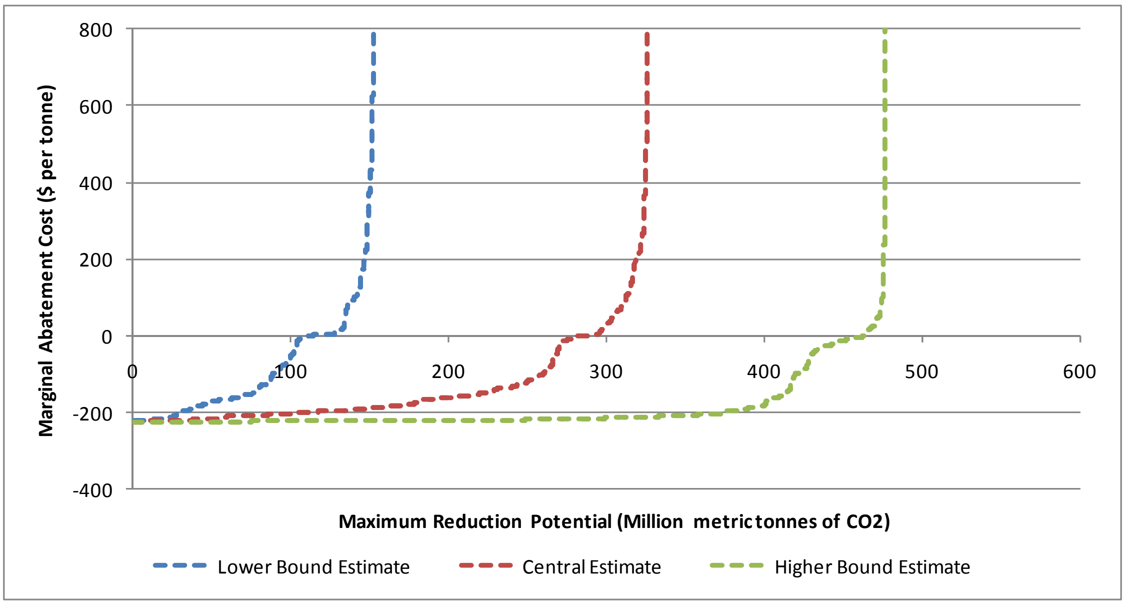

Figure 6-2: Aggregated MACC in 2020 with $700 per ton fuel price and 10% discount rate for all ship types (without speed reduction)

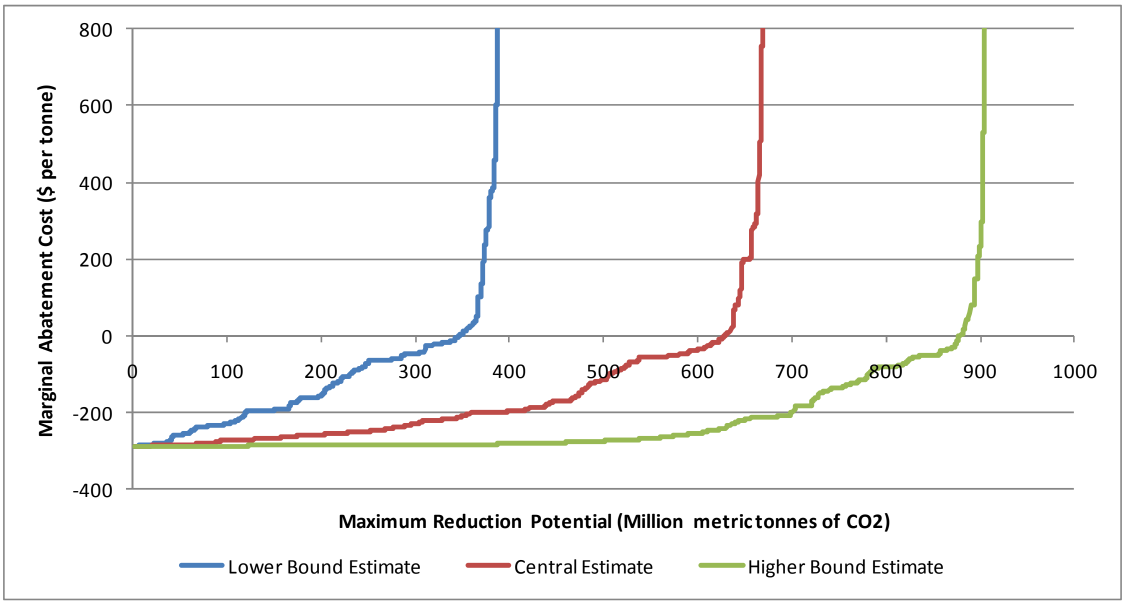

Figure 6-3: Aggregated MACC in 2030 with $900 per ton fuel price and 10% discount rate for all ship types

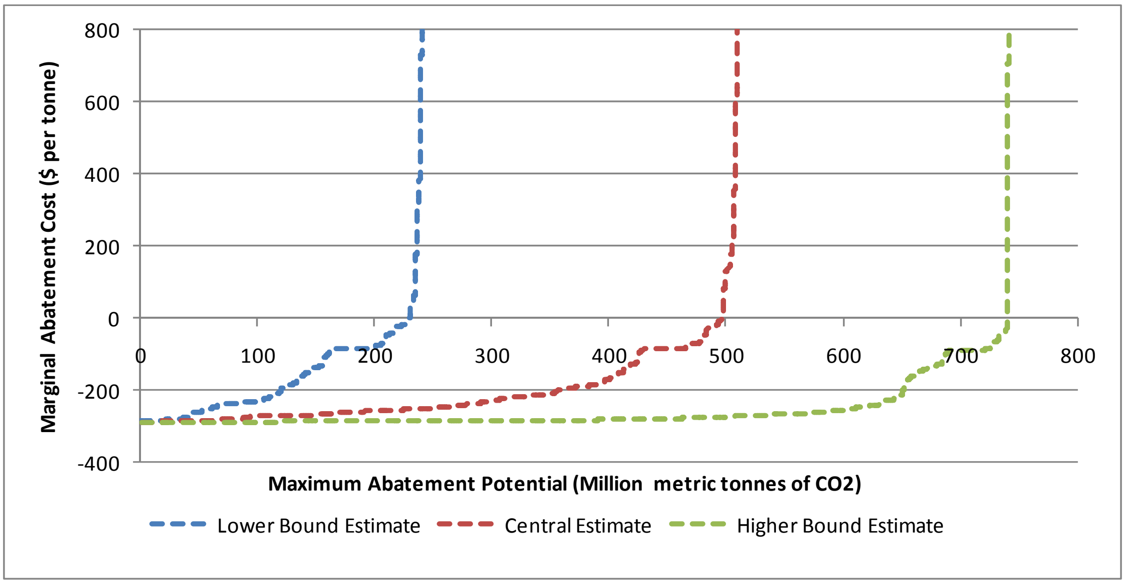

Figure 6-4: Aggregated MACC in 2030 with $900 per ton fuel price and 10% discount rate for all ship types (without speed reduction)

6.14 The MACCs show two interesting results. First, there is a considerable potential to reduce emissions. The reduction is 166% and 74% of projected CO2 growth between 2007 and 2020 and between 2007 and 2030, respectively. Even if all measures included in the MACC would be implemented, total emissions would decrease by 17% and increase by 23% in 2030. Second, a major share of the 2020 emission reductions can be achieved at negative marginal abatement costs, i.e. at a net savings. In this respect, it should be noted that the MACCs were calculated against a frozen technology baseline. These show that the measures evaluated here create an opportunity to improve the efficiency of ships relative to the current fleet average efficiency. Moreover, the negative costs are highly sensitive to projected future fuel prices, as shown below.

6.15 In Figure 6-5 and Figure 6-6, the aggregated MACC of all new-build ships (without discriminating by size) with and without speed reduction are shown. In Figures 6-5, "EEDI related" means that the changes shown would be reflected in the EEDI calculation as currently proposed by installing a smaller main engine. Therefore, speed reduction is considered an "EEDI related" measure (i.e., a "design" related measure) for "newbuild" ships. For existing ships, speed reduction is treated as an "operational" measure elsewhere in this report. To estimate the energy efficiencies and cost-effectiveness of speed reductions for new builds we use operational speed reductions as a proxy for installing smaller engines. Appendix IV provides these MACC for all 14 ship types without discriminating by size. The model allows for the calculation of these MACC for all vessel type / size combinations for both new builds and existing ships. The algorithm used to calculate these MACCs can be parsed to identify the efficiency measures comprising these curves.

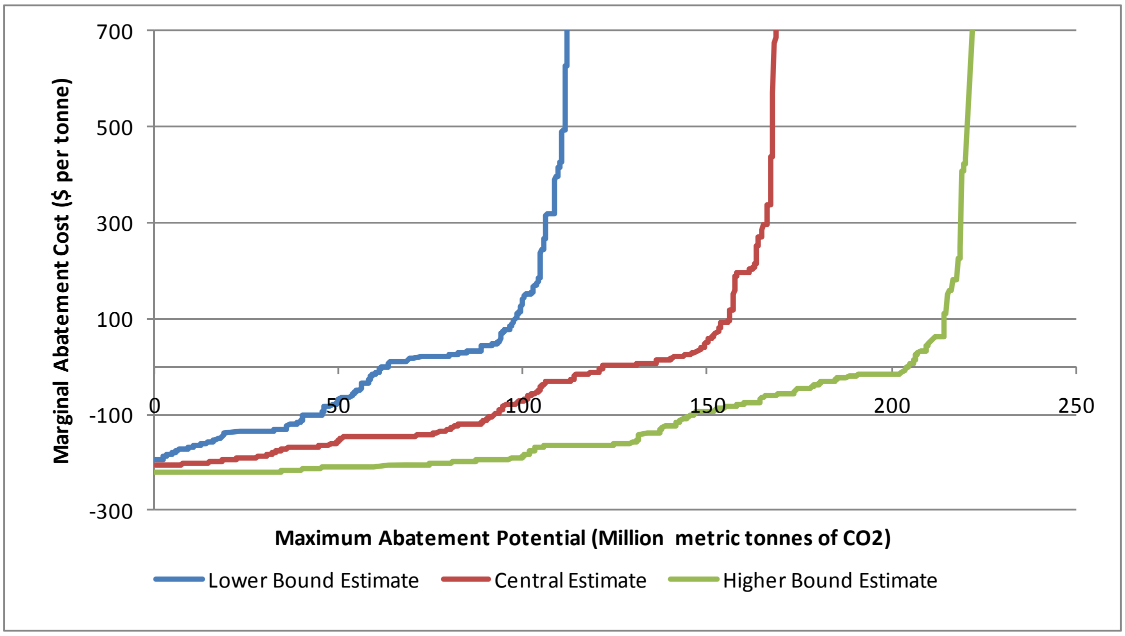

Figure 6-5: The aggregated EEDI related MACC of all new-build ships with speed reduction.

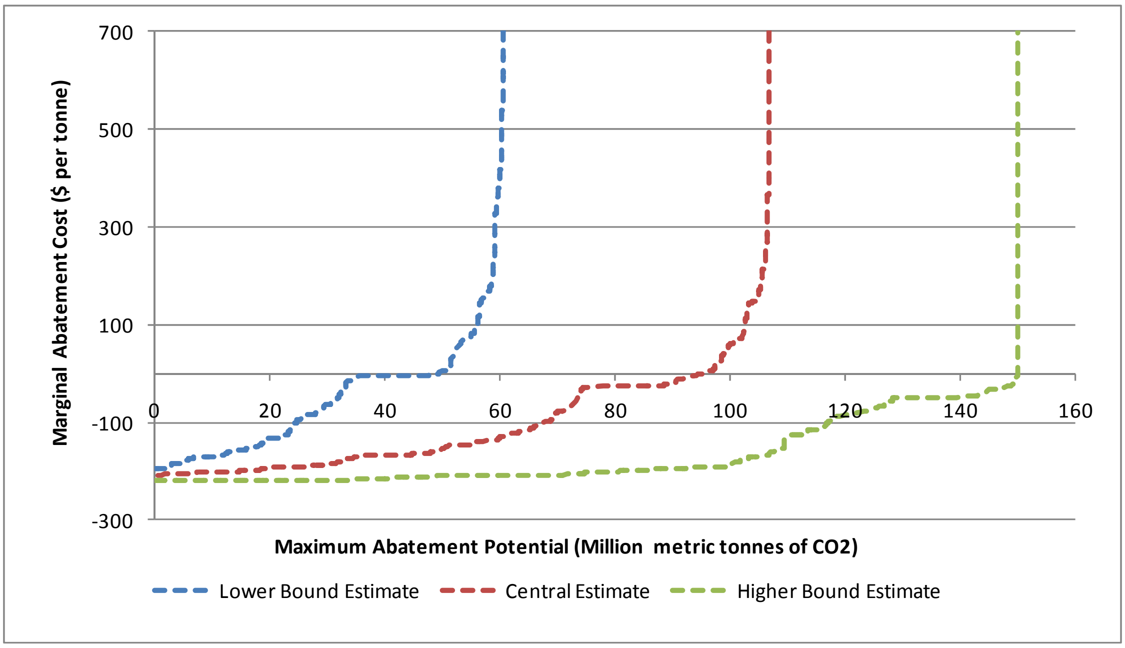

Figure 6-6: The aggregated EEDI related MACC of all new-build ships without speed reduction.

Sensitivity to discount rate and fuel prices

6.16 Figure 6-7 and Figure 6-8 show that the cost-effectiveness of the measures are not significantly influenced by the change of the discount rates, especially for the measures which have negative costs. For these measures, fuel savings probably play a larger role.

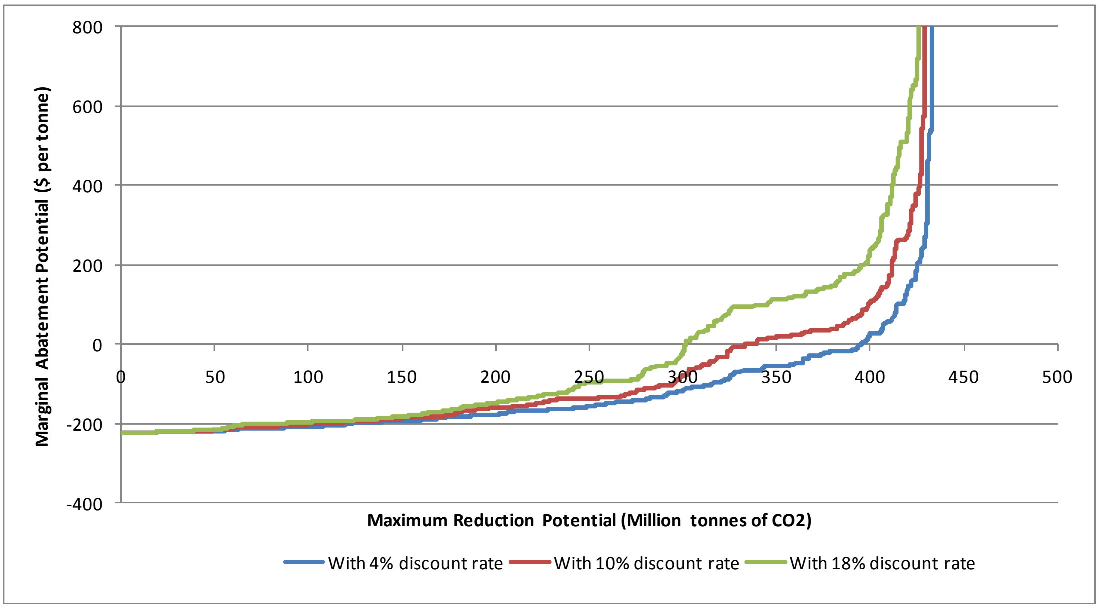

Figure 6-7: Sensitivity analysis of the discount rate in 2020 for all ship types

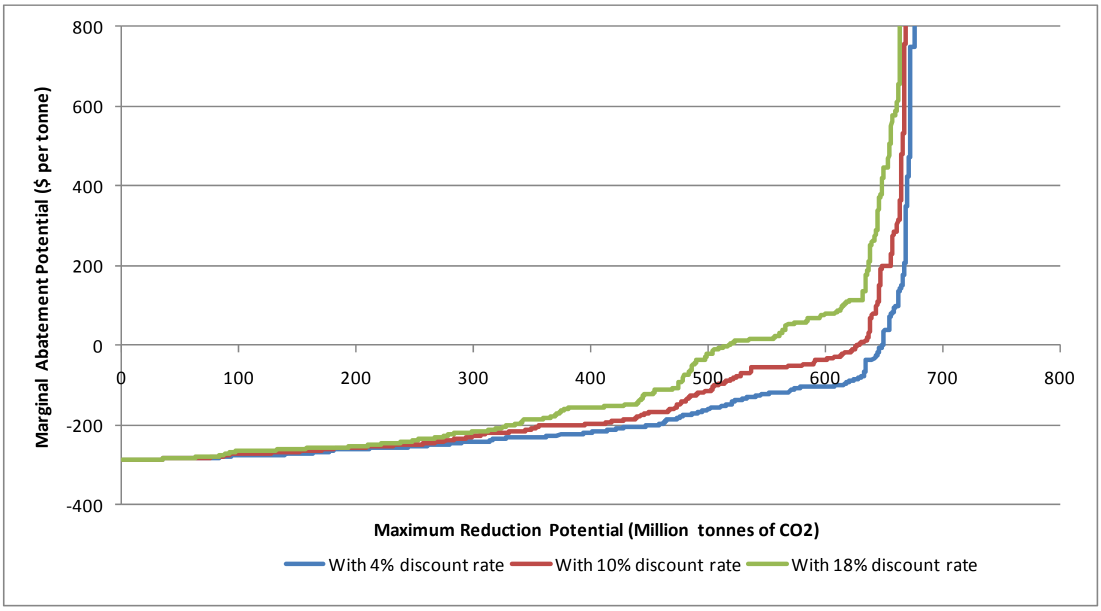

Figure 6-8: Sensitivity analysis of the discount rate in 2030 for all ship types

6.17 Figure 6-9 and Figure 6-10 demonstrate that the MACC shifts downward with increasing fuel prices. With higher fuel prices, more emissions would be reduced by measures with negative costs. This suggests higher fuel price would encourage the industry to use energy-saving measures. The higher fuel prices also make more sense for ship owners and operators to employ energy-saving options for their ships with lifetime is much shorter than the abatement measure.

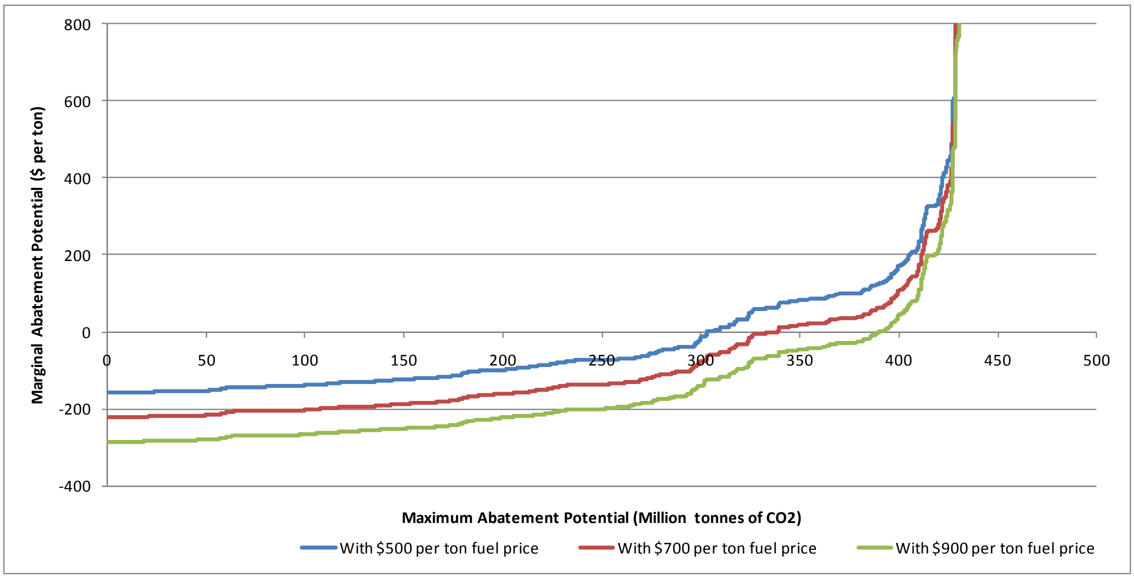

Figure 6-9: Sensitivity analysis of fuel price in 2020

Figure 6-10: Sensitivity analysis of fuel price in 2030

The Marginal Abatement Cost Curve by Ship Types

6.18 While it is useful and necessary to show the aggregated MACC, breaking the MACC down by ship types may be helpful to provide more insights, because each type of ships has different characteristics. Figures 6-11, 6-12 and 6-13 show three examples of the MACC of crude tankers, bulkers, and containerships in 2020 with $700 per ton fuel price and 10% discount rate. For other 11 ship types, their MACCs in 2020 are shown in the Appendix IV. Figure 6-14 to Figure 6-16 show the MACC for new built tanker, bulker, and containership. Detailed comparisons are made to compare the MACC of new-builds and all ships for other types of ships. These MACC can be downloaded from http://www.theicct.org/marine/ and http://www.sname.org/SNAME/climatechange/MACreport .

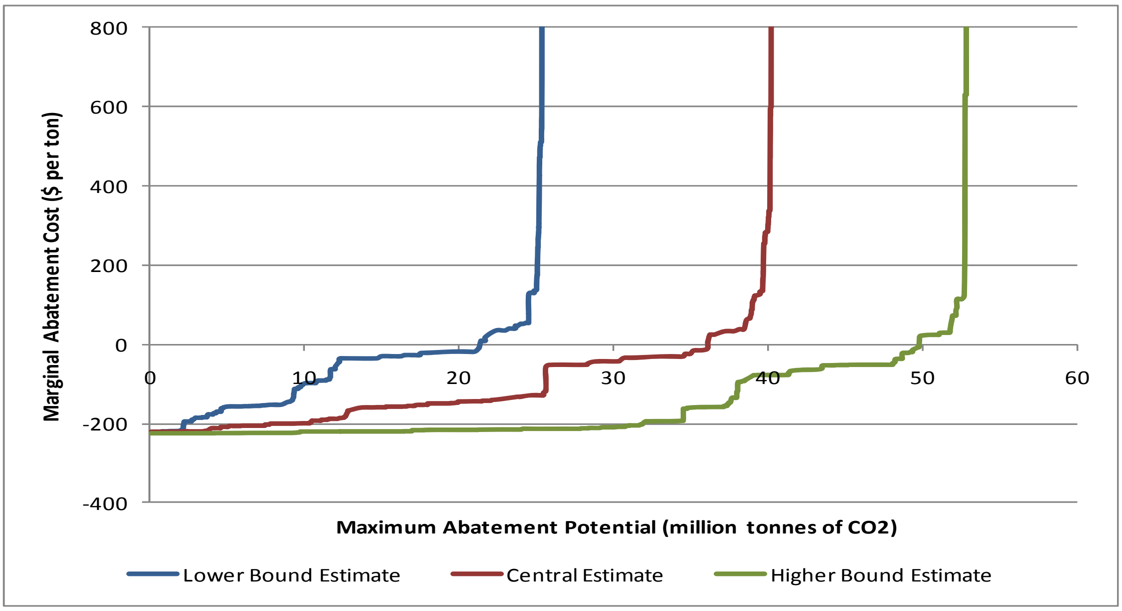

Figure 6-11: MACC for crude tankers in 2020

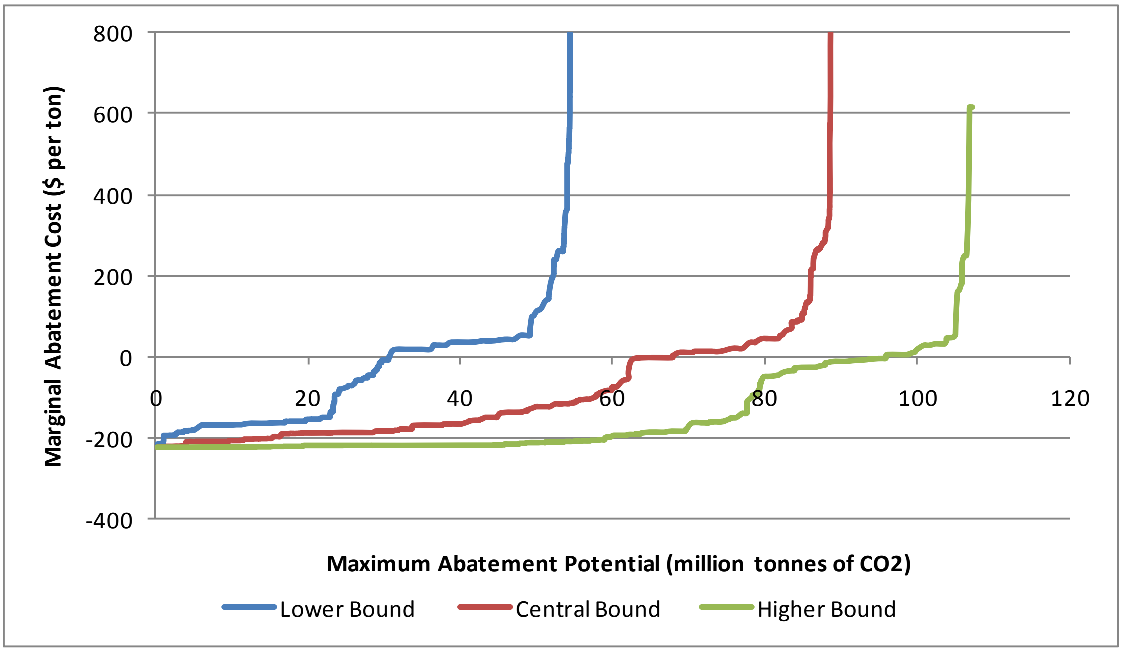

Figure 6-12: MACC for bulkers in 2020

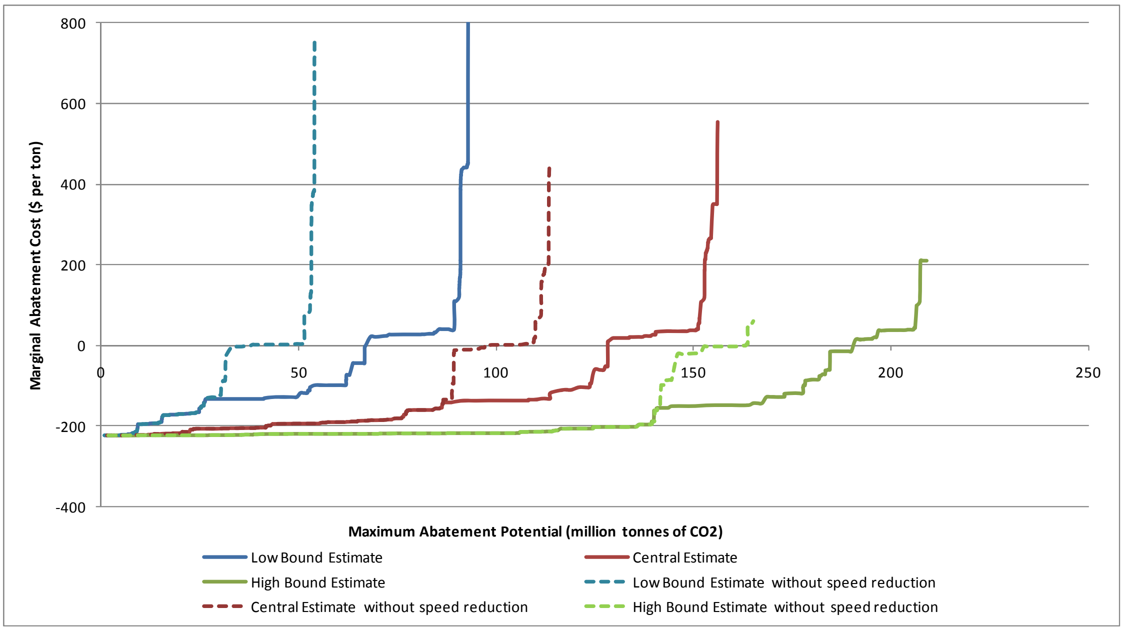

Figure 6-13: MACC for containerships in 2020 with and without speed reduction

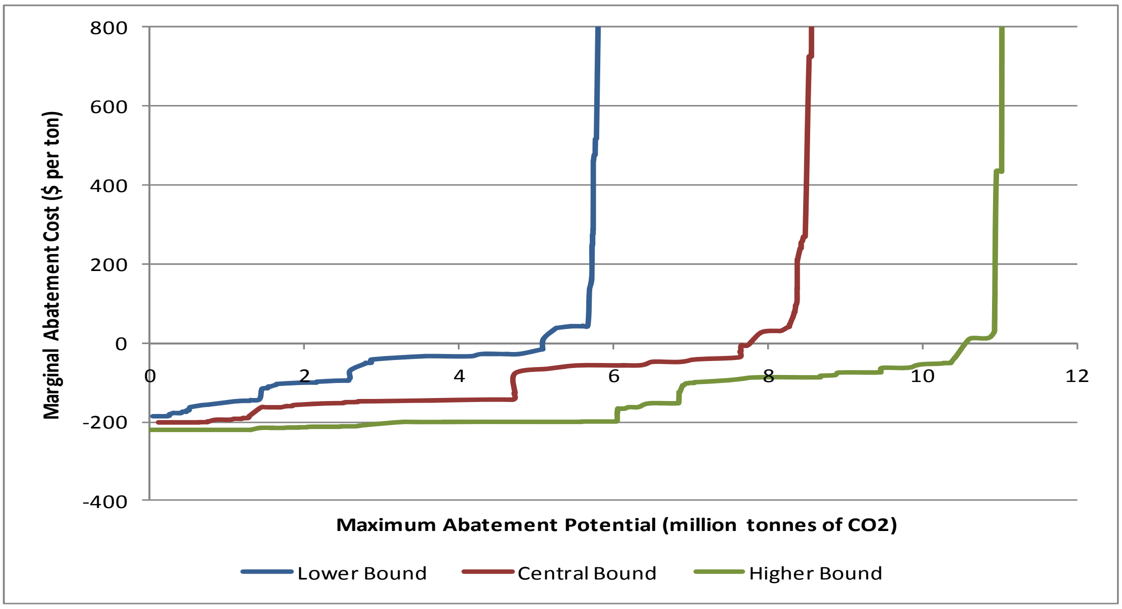

Figure 6-14: EEDI related MACC for new-build crude tankers

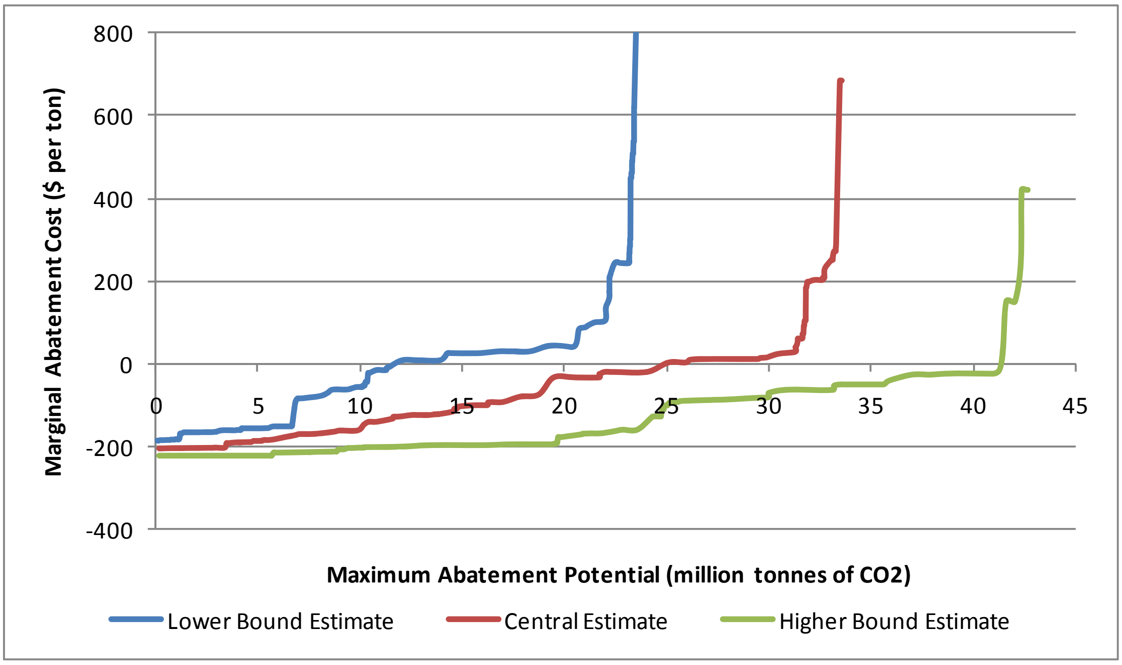

Figure 6-15: EEDI related MACC for new-built bulkers

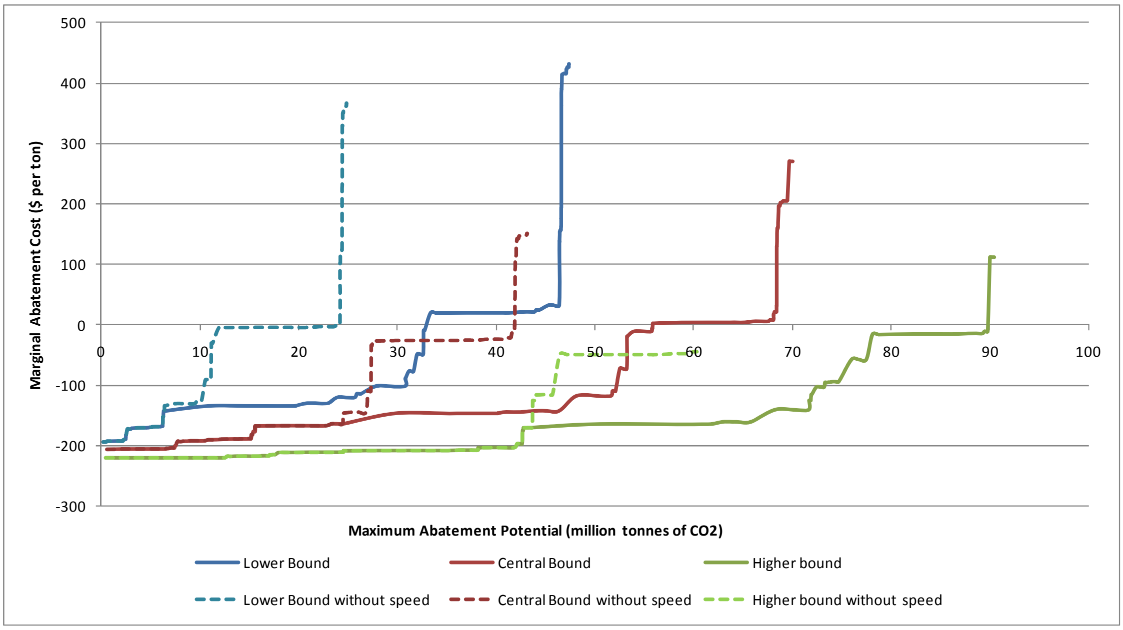

Figure 6-16: EEDI related MACC for new-built containerships with and without speed reduction

6.19 In Figures 6-5, 6, 14, 15, and 16, "EEDI related" means that the changes shown would be reflected in the EEDI calculation as currently proposed by installing a smaller main engine. Therefore, speed reduction is considered an "EEDI related" measure (i.e., a "design" related measure) for "newbuild" ships. For existing ships, speed reduction is treated as an "operational" measure elsewhere in this report. To estimate the energy efficiencies and cost-effectiveness of speed reductions for new builds we use operational speed reductions as a proxy for installing smaller engines. We can infer from these graphs that speed reduction (through smaller engines for new ships and speed reductions for ships in service) can account for a significant proportion of cost –effective increased energy-efficiency.

6.20 As shown above, marginal abatement curves (MACC) for 14 ship types were developed and analyzed. MACC are developed by aggregating mutually independent energy-improvement technology measures and plotting the cost-effectiveness of individual measures for separate ship categories against the corresponding CO_2 emissions reductions potential. MACCs are highly dependent on speed reduction as a measure. For example, when speed reductions were eliminated as a design option for containerships in 2020, the central estimate for CO_2 emissions reduction potential was almost 24% less than when it is included at zero net cost. (In this study the 2020 estimated cost of fuel was $700/ton.) This estimate excluded all non-speed reduction operational measures and assumes that the speed-reduction operational measures identified in this report are a proxy for design speed reductions all else being constant. Other operational measures accounted for about 2-3% of potential emissions reduction at net MAC of zero or no net cost. Similar results (both in absolute and relative terms) were estimated from most other ship types. MACC graphs for the 14 vessel types are presented in Appendix V that show the cumulative estimated MAC and emissions reduction potential with and without operational measures. Speed reductions accounted for most of the operational emissions reductions.

CHAPTER 7

CONCLUSIONS

7.1 This report had two primary purposes. The first was to develop a standardized methodology for examining energy-efficiency improvement measures on ships. The methodology was designed to estimate the cost-effectiveness and CO_2 emissions reduction potential of each measure. The second objective of this report was to apply the methodology to the twenty-two (22) abatement measures for which data was available. The data on the cost, reliability, variability, and effectiveness of each abatement measure was obtained from published sources including both manufacturers and other studies. We attempted to corroborate this data with direct interviews of operators and others with experience with the measures. However, further work needs to be done on the actual in-service cost, reliability, variability, and effectiveness of these measures. SNAME's Technical & Research Committee will continue to evaluate these measures. This analysis provided estimates of CO_2 emissions reduction potential and associated marginal abatement costs for 14 types of new and existing ships as defined by the IMO GHG Experts Group. For each vessel type, size, and age, these cost estimates were plotted against estimated CO_2 emissions reduction potential and the marginal abatement cost curves for each ship type were presented. Sensitivity analyses were also performed to examine the impact of fuel prices and discount rates on the cost effectiveness of the measures. To avoid complexity, all costs are in USD$; and emission reductions are in metric tonnes CO_2. This study did not assume that ship owners and operators would make the investments or employ the specific operational measures, but just demonstrated what the estimated costs and benefits would be if the necessary investment(s) were made. The report strives to present these estimates in an accessible format. Key findings should be of interest to policy makers, ship owners and operators, and other interested parties.

7.2 This report describes fifty (50) technical and operational energy-efficiency improvement measures and presents a detailed analysis of twenty-two (22) of these measures for which we could obtain data.

.1 The analysis includes an assessment of the cost effectiveness and abatement potential of each measure (often presented as a range). We included reviewed earlier studies and identified additional energy efficiency improvement measures, and incorporated incorrectly categorized measures as supporting means of measures (e.g., hull monitoring supports hull cleaning and polishing).

.2 The applicability of each measure was determined for new and existing vessels and fourteen (14) ship types by size and age (a total of three hundred eighteen (318) combinations).

.3 Implementation barriers and strategies to address these barriers are described in this report.

.4 A basis for projecting and applying the learning rate for new technologies was developed and used in future cost estimates

.5 The measures were grouped (fifteen (15) groups) to ensure that similar measures were identified as mutually exclusive so as not to overestimate the energy-efficiency improvement potentials of employing multiple measures.

.6 We reviewed data on costs and abatement potential and the applicability to both new and existing ships of individual measures and cross-checked it with ship owners and operators, naval architects and marine engineers.

.7 We closely examined key assumptions on for example current and future fuel prices and discount rates. We explicitly described assumptions and methodology in order to present a transparent analysis.

.8 We estimated the cost effectiveness of measures for both new and existing ships as a function of ship size and for existing ships by age.

.9 We developed marginal abatement cost curves as a function of ship type for new and existing ships and examined the role of measures such as speed reductions on MACC estimates.

.10 We analyzed MACC as a function of ship type and identified a wide range in net marginal abatement costs and ship type. An analysis of the cost effectiveness of energy-efficiency improvement measures suggests significant differences as a function of ship type, size and vessel age.

7.3 For each measure and for each vessel type by size and by age, where the measure is appropriate, low and high estimates of the cost-effectiveness to employ the measure were estimated. The range of estimates reflects different operating patterns of vessels and uncertainty about the cost and abatement potential of individual measures. These estimates of cost effectiveness are for a high emissions reduction potential and a low emissions reduction potential. For each reduction potential, there is one high cost estimate and one low cost estimate. The low and high reduction potentials are associated with the ranges and uncertainty of both the cost effectiveness and the energy-efficiency improvement potential for each measure. Appendix II contains estimates for ships and as a function of ship type, size and age. The methods and assumptions to estimate the cost effectiveness are described in detail. Key factors about each measure were analyzed, as well as implementation decision making by the ship owner or operator including but not limited to cost effectiveness, capital and opportunity costs, pay-back periods, and discount and freight rates.

7.4 In turn, marginal abatement costs curves (MACC), resulting from the analysis are presented in this report for new construction for the fourteen ship types. The MACC plot marginal abatement costs against CO_2 emissions reductions. These MACC were based on a rank ordering of the measures or group of measures based on the cost effectiveness and the appropriateness of the measure to a specific ship type and size, including impact on percent (%) emissions reduction, ease of implementation, and other factors. The cost-effectiveness of individual measures was summed to develop marginal abatement cost curves. These MACC are graphically presented in this report with high, central and low estimates for the fourteen ship types. The specific measures which make up each MACC estimate are transparent.

7.5 The cost effectiveness and the estimates and CO_2 emissions reduction potential for each measure vary widely as a function of ship type, size, and age. We depict this by providing low and high estimates. A range is given because of the uncertainty with respect to the costs and abatement potential. The aggregation of these costs when estimating the net abatement potential using marginal abatement curves similarly shows that the costs and abatement potential vary widely among types of ships. In particular, when aggregating cost effectiveness estimates for measures to develop MACC curves, analysts should be attentive to the impact that that certain measures have by ship types that impacts the net costs and potential of efficiency improvements. For example, speed reductions for containerships have a greater potential for emissions reduction relative to slower moving vessels and most other measures.

7.6 The cost effectiveness analysis examined both new and existing ships. One of the most striking findings is that the MACC for 2020 and 2030 show a considerable abatement potential at negative costs: meaning that many of these measures are profitable (i.e., show a positive net present value) on both new and existing ships. This finding is consistent with other MACC studies for maritime transport, though this study also looked at existing ships and is also consistent with current industry practice (i.e., implementation on existing ships). The interpretation of these findings requires careful consideration.

.1 First, considerable cost savings and CO_2 emissions reduction can accrue now and through 2020 and beyond for existing ships.

.2 Second, the meaning of this finding is that by 2020 and 2030, the energy-efficiency of the world fleet may be improved considerably while lowering transport costs, assuming that fuel prices will continue to rise in real terms and that demand for maritime transport will continue to grow.

.3 And third, of the 50 measures identified we were only able to analyze 22 as we had insufficient data to assess these other measures.

7.7 Net abatement costs and the corresponding CO_2 reduction potential are highly dependent on speed reduction as a measure. For example, when speed reductions are eliminated as a design option for containerships in 2020, the central estimate for CO_2 emissions reduction potential is almost 24% less than when it is included at the same net marginal abatement costs of zero or more simply at no net cost. This estimate excludes all non-speed reduction operational measures and assumes that the speed-reduction operational measures identified in this report are a proxy for design speed reductions all else being constant. Other operational measures account for about 2-3% of potential emissions reduction at net MAC of less than zero, or at a net cost savings or zero net cost. Similar, though not as dramatic results (both in absolute and relative terms) are expected from most other ship types.

7.8 We found that operational abatement measures have a significant potential to reduce emissions, as do technical measures. As noted, speed reduction accounts for a significant proportion of many of the estimated operational CO_2 emissions reductions. As well, speed reduction achieved through the installation of lower powered main propulsion is considered an "EEDI related" measure (i.e., a "design" related measure) for "newbuild" ships. For existing ships, speed reduction is treated as an "operational" measure elsewhere in this report. To estimate the energy efficiencies and cost-effectiveness of speed reductions for new builds we use operational speed reductions as a proxy for installing smaller engines. We infer from our analyses that speed reduction (through smaller engines for new ships and speed reductions for ships in service) can account for a significant proportion of cost –effective increased energy-efficiency.

7.9 Of the 22 measures we analyzed, several have limited potential application to certain ship types and others may not be appropriate for existing ships. The potential cost effectiveness for some measures varies widely and may not be cost effective in some circumstances.

7.10 These 22 measures, however, can achieve significant CO_2 reductions in 2020 and 2030 for existing ships and new ships, both individually and collectively, many at a net cost savings to the ship owner / operator.

7.11 A large number of operational and technical measures may be applied to improve the fuel-efficiency of existing and new ships. Many of these measures would become cost effective when fuel prices increase as predicted. As a result, we projected that over 436 Mt CO_2 emissions can be reduced through fuel-efficiency improvements by 2020 and by almost 677 Mt by 2030.

7.12 We discussed an important concern with EEDI. One of the biggest concerns with EEDI is that the most direct way to capture efficiency gains through hull/propeller optimization is by installing smaller engines (i.e., reduced horsepower) as EEDI is based on the Maximum Continuous Rating (MCR) of the main engines. Installing lower horsepower main engines may reduce the safety margin for vessels operating in heavy seas. We discussed the potential to reduce safety margins for vessels in heavy seas by using less powerful engines or engines that can deactivate cylinders (so as to have available reserve power for safety considerations.

7.13 We developed an example of how the designer can optimize the EEDI with the application of a hull coating that can improve energy efficiency. During the design phase, the designer may specify that a specific hull coating be applied. The net improvement in energy efficiency by the specification of the hull coating could translate into an optimized EEDI through the installation of a smaller engine. If applied after design but prior to the sea trial, this could result in a higher design speed at the installed engines power rating, thus reducing the vessel's attained EEDI.

7.14 The outcome of this report does not favour a particular market-based approach, or specific energy efficiency standards. The methodologies and analysis are structured to support the development and implementation of any regulatory and/or corporate policies that may be adopted. As well we expect that the results may be used by ship designers, builders, owners and operators as a tool in their decision making to employ one or more technologies or operational measures. The methodology and inputs are structured such that each can be varied should new information be incorporated or to posit and test different views on any of our assumptions.

7.15 The approach allows policy makers and others to factor new or different information about measures and/or basic assumptions easily. As the report provides and documents the assumptions and input data, as well as an easy to follow and replicate approach, expanded or revised analysis can be accomplished quickly in a standardized manner. In turn, these can provide customized cost-effectiveness estimates for a suite of selected measures and specific ship type, size and age, and in turn may be used to derive customized MACC.

7.16 The cost-effectiveness of measures and MACCs presented in this report can be used for a number of purposes.

.1 Improve the projections of future emissions. Emission projections can be based on projections of increased demand and energy-efficiency improvement estimates. In many studies, efficiency improvement estimates are based on historical data or on expert judgement. By using a MACC to estimate energy-efficiency improvements, more accurate projections can be made, incorporating fuel price projections and other variables. In turn, our methodology can easily provide estimated gross CO_2 reductions by ship type, size, and age or any combination or aggregation thereof, for any policy assessment scenario under consideration.

.2 Improve policy design choices. Some policies may incentivize one set of measures, while other policies may take another set into account. Some policies may affect some ship owners and operators more than others or some ship types more than others. The cost-effectiveness of measures and MACC presented in this report allow policy makers to make an informed choice about which measures to include in the governmental and company policy options. They also allow them to identify which segments of the shipping industry or an owner's fleet are affected by the policies as well as the extent.

.3 Assist in the assessment of policies. MACC and corresponding estimates of the CO_2 emission reduction potential may be used to analyse the costs, effects and cost-effectiveness of policy instruments. They can be used to assess the costs imposed on the shipping sector by efficiency standards, the in-sector abatement incentivized by fuel levies or cap-and-trade schemes, and the costs and effects of baseline-and-credit trading schemes. The marginal abatement cost curves in particular can be used to.

.4 Support cost/benefit analysis for future regulation of the international maritime industry.

.5 Understand how the different parts of the industry will be affected by mandated and increasing energy-efficiency/CO_2 emissions reduction requirements.

.6 Understand how a vessel owner or operator decides energy efficiency measures to do first, and when to employ a measure (e.g., opportunity costs, barriers, importer/shipper expectations).

.7 Contribute to cost-benefit analyses of climate policies for shipping. By clarifying the relation between costs and effects, MACC are a crucial element of any cost-benefit analysis of policies. And to.

.8 Assist ship owners and operators in the selection of abatement measures. An overview of the cost-effectiveness of different measures and combinations of abatement measures helps ship owners and operators to select measures that may be of interest to them, thus limiting the search costs and increasing the efficiency of shipping.

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APPENDIX I

DISCUSSION OF EEDI AS IT RELATES TO ABATEMENT MEASURES

Options for Decreasing EEDI

A1.1 This Appendix is based in large part on the work of the Society of Naval Architects and Marine Engineers' Technical and Research Committee ad hoc panel on Green House Gases and Energy Efficiency, "*An Evaluation of the Energy Efficiency Design Index (EEDI) Baseline for Tankers, Containerships, and LNG Carriers"*, SNAME Symposium, Climate Change and Ships: Increasing Energy Efficiency, Feb. 16-17, 2010. Larkin, J. *et al* (2010), with funding by the American Bureau of Shipping and Herbert Engineering. The results of that study were presented to IMO as MEPC60/4/33 and MEPC 60/4/34.

$$\frac{\left(\prod_{j=1}^{M} f_j\right)\left(\sum_{i=1}^{nME} P_{ME(i)} \cdot C_{FME(i)} \cdot SFC_{ME(i)}\right) + \left(P_{AE} \cdot C_{FAE} \cdot SFC_{AE}*\right) + \left(\left(\prod_{j=1}^{M} f_j \cdot \sum_{i=1}^{nPTI} P_{PTI(i)} - \sum_{i=1}^{neff} f_{eff(i)} \cdot P_{AEeff(i)}\right) C_{FAE} \cdot SFC_{AE}\right) - \left(\sum_{i=1}^{neff} f_{eff(i)} \cdot P_{eff(i)} \cdot C_{FME} \cdot SFC_{ME}\right)}{f_i \cdot Capacity \cdot V_{ref} \cdot f_w}$$

Re: MEPC .1/ Circ. 681, "Interim Guidelines on the Method of Calculation of the Energy Efficiency Design Index for New Ships."

Explanation of Terms and Potential to Decrease EEDI

Conversion Factors (C_{FME} and C_{FAE})

A1.2 Conversion factors are given for five categories of fuels used in the marine industry. The conversion factors were selected to be consistent with the Energy Efficiency Operator Indicator (EEOI) and the International Panel on Climate Change (IPCC) emission factors. The factors give the equivalent mass emission of CO_2 from combustion of a given mass of fuel. Specific values for fuel carbon contents and complete combustion are assumed. The type of fuel used in the calculation should be the same as the fuel burned in the determination of the specific fuel consumption on the Engine International Air Pollution Prevention (EIAPP) certificate.

Specific Fuel Consumption (SFC_{ME} and SFC_{AE})

A1.3 Specific fuel consumption (SFC) is divided into two categories: main engine and auxiliary engine fuel consumption. Main engine fuel consumption is the SFC reported on the EIAPP Certificate for the parent engine in accordance with the NO_x Technical Code at 75% of the Maximum Continuous Rating (MCR). Auxiliary engine fuel consumption is the fuel consumption reported on the parent engine's EIAPP Certificate at 50% of the MCR. If different sized auxiliary engines are used, a single SFC is entered into the equation by taking the weighted average of the different engines.

Potential to decrease EEDI

A1.4 Decrease SFC by increasing main and auxiliary engine efficiencies. For example (Larkin, *et al*, 2010):

The B&W MAN ME series engines which are arranged with electronically controlled fuel valves and exhaust valves represent the state of the art in slow speed diesel design. The ME series of electronically controlled engines have specific fuel consumption (SFC) values that are equal to the mechanically controlled engines at the optimizing point, but lower over a wide range of powers because the electronic controls can match fuel and exhaust setting to the engine load. Figure A1-1 shows the relative performance of an electronically controlled engine and a mechanically controlled engine optimized for the 100% MCR point.

The ability to match fuel and exhaust settings to load allows better control of emissions over a wider range of power. Although the ME series of engines presently cost more than the MC engines (approximately 10% premium), it is anticipated that this premium will decrease over time.

As shown in Table A1-1 the electronically controlled ME series engines provide a 2.2% improvement in the EEDI as compared to the mechanically controlled MC series engines.

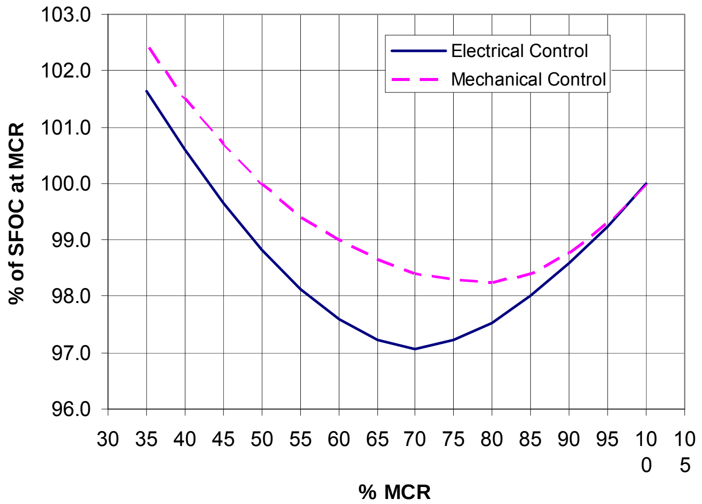


Figure A1-1: Specific Fuel Consumption of Mechanically Controlled and Electronically Controlled Two-Stroke Diesel Engines (Larkin et al, 2010)

Table A1-1: Influence of Electronic Engines on the EEDI (Larkin et al, 2010)

		Standard Design w/ MC engine	with ME engine
Panamax	MAN B&W ME Model	6S50MC-C8	6S50ME-C8
	RPM	127	127
	SFC at 75% MCR (g-kWhr)	177.3	173.3
	Attained EEDI ($EEDI_A$)	5.948	5.822
	Baseline EEDI ($EEDI_{BL}$)	6.110	6.110
	$\%EEDI = (EEDI_A / EEDI_{BL}) - 1$	-2.7%	-4.7%
	% Change vs. Standard Design	---	-2.1%
Aframax	MAN B&W ME Model	6S60MC-C8	6S60ME-C8
	RPM	105	105
	SFC at 75% MCR (g-kWhr)	176.3	172.3
	Attained EEDI ($EEDI_A$)	3.727	3.647
	Baseline EEDI ($EEDI_{BL}$)	3.864	3.864
	$\%EEDI = (EEDI_A / EEDI_{BL}) - 1$	-3.5%	-5.6%
	% Change vs. Standard Design	---	-2.2%
Suezmax	MAN B&W ME Model	6S70MC-C8	6S70ME-C8
	RPM	91	91
	SFC at 75% MCR (g-kWhr)	176.3	172.3
	Attained EEDI ($EEDI_A$)	3.140	3.072
	Baseline EEDI ($EEDI_{BL}$)	3.187	3.187
	$\%EEDI = (EEDI_A / EEDI_{BL}) - 1$	-1.5%	-3.6%
	% Change vs. Standard Design	---	-2.2%
VLCC	MAN B&W ME Model	7S80MC-C8	6S80ME-C9
	RPM	78	78
	SFC at 75% MCR (g-kWhr)	175.3	171.2
	Attained EEDI ($EEDI_A$)	2.529	2.473
	Baseline EEDI ($EEDI_{BL}$)	2.316	2.316
	$\%EEDI = (EEDI_A / EEDI_{BL}) - 1$	9.2%	6.8%
	% Change vs. Standard Design	---	-2.2%

Correction Factors (f_i, f_j, and f_w)

A1.5 The correction factor f_i accounts for ship specific design elements and the factor, f_j, accounts for any technical or regulatory limit on capacity. Currently, these factors are only used for ships designed with an ice class notation. f_w is a factor representing the decrease in speed in certain sea conditions.

Speed (V_{ref})

A1.6 The speed used in the EEDI is the vessel's speed when operating at a draft corresponding to the specified capacity, at a trim as defined by the corresponding condition specified in the approved stability booklet. The speed assumes the vessel is operating at power level P_{ME}, in deep water and in calm weather (no winds or waves). The EEDI is particularly sensitive to the service or design speed, as the required power increases by roughly the cube of the variation in service speed ($P \propto V^3$). Reducing service speed by one knot reduces the EEDI by between 10% and 15%.

Potential to decrease design speed

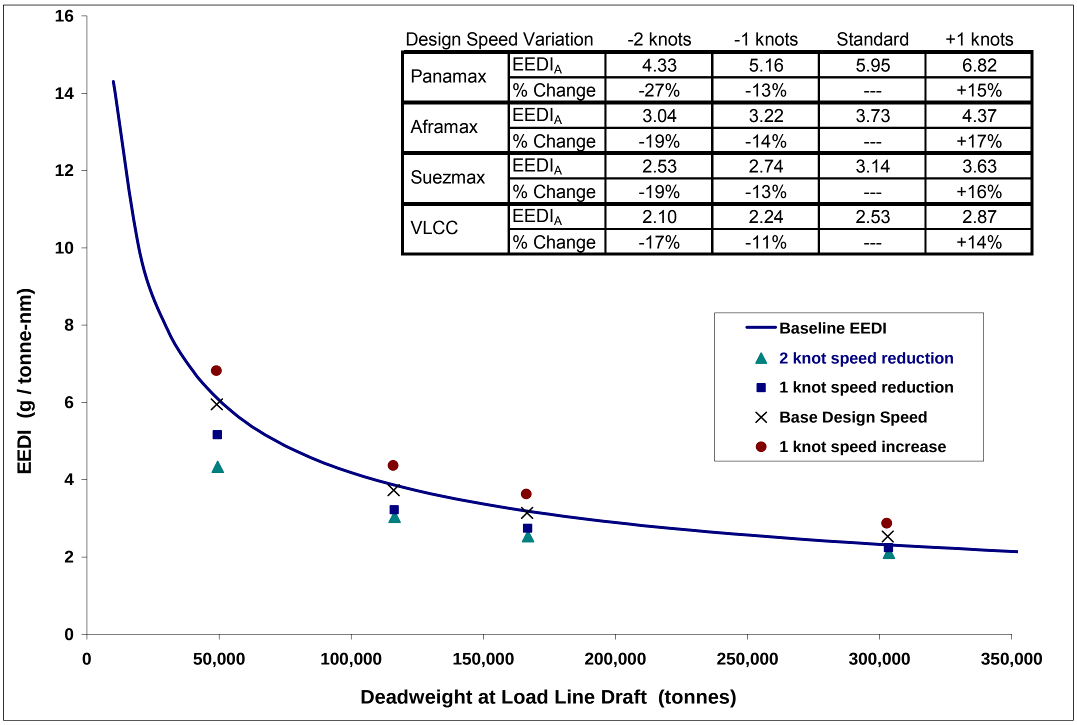
A1.7 Examples of how this relates to change in design speed for tankers and container ships follow. (Larkin et al, 2010) Note however that the design speed for tankers is about 15 knots, for container ships 24-28 knots. There is less opportunity for reductions in design speed for tankers than for containerships.

Design Speed for Tankers

A1.8 As shown in Table A1-2 and Figure A1-2, increasing speed by 1 knot increases the EEDI by 14% to 17%, whereas reducing the speed by 1 knot reduces the EEDI by 11% to When assessing the powering requirements, the most suitable MAN B&W engine was selected for each scenario. The engine is assumed to be de-rated to the power required to attain the design speed at 15% sea margin with the main engine operating at 90% MCR. The smaller engines associated with the slower service speeds may have higher rpm's. The propulsive coefficient is reduced at the higher rpm which somewhat mitigates the benefits of the lower service speed. Table A1-3 shows the selected main engines, % de-rating, and the associated SFC and RPM values that are applied for this matrix of tanker designs and speeds. Note that the SFC values assume the engine at 75% MCR, burning MDO under ISO conditions. A 3% margin above published SFC figures is included to reflect the anticipated difference between the published values and those shown in the EIAPP Certificates.

Table A1-2: Influence of Service Speed on EEDI for Standard Oil Tankers (Larkin et al, 2010)

Design Speed Variation		-2 knots	-1 knots	Standard	+1 knots
Panamax	Service Speed (design)	12.90	13.90	14.90	15.90
	DWT at SLL draft (tonnes)	49,498	49,360	49,203	49,039
	Main Engine MCR (kW)	5,685	7,291	9,222	11,361
	Attained EEDI ($EEDI_A$)	4.33	5.16	5.95	6.82
	Change vs. Standard Design	-27%	-13%	---	+15%
Aframax	Service Speed (design)	13.20	14.20	15.20	16.20
	DWT at SLL draft (tonnes)	116,453	116,337	116,135	115,889
	Main Engine MCR (kW)	9,564	11,073	13,822	17,378
	Attained EEDI ($EEDI_A$)	3.04	3.22	3.73	4.37
	Change vs. Standard Design	-19%	-14%	---	+17%
Suezmax	Service Speed (design)	13.20	14.20	15.20	16.20
	DWT at SLL draft (tonnes)	166,951	166,801	166,576	166,308
	Main Engine MCR (kW)	11,878	13,940	17,185	21,260
	Attained EEDI ($EEDI_A$)	2.53	2.74	3.14	3.63
	Change vs. Standard Design	-19%	-13%	---	+16%
VLCC	Service Speed (design)	13.80	14.80	15.80	16.80
	DWT at SLL draft (tonnes)	303,509	303,320	303,032	302,699
	Main Engine MCR (kW)	19,165	22,097	26,736	32,376
	Attained EEDI ($EEDI_A$)	2.10	2.24	2.53	2.87
	Change vs. Standard Design	-17%	-11%	---	+14%



Design Speed Variation		-2 knots	-1 knots	Standard	+1 knots
Panamax	$EEDI_A$	4.33	5.16	5.95	6.82
	% Change	-27%	-13%	---	+15%
Aframax	$EEDI_A$	3.04	3.22	3.73	4.37
	% Change	-19%	-14%	---	+17%
Suezmax	$EEDI_A$	2.53	2.74	3.14	3.63
	% Change	-19%	-13%	---	+16%
VLCC	$EEDI_A$	2.10	2.24	2.53	2.87
	% Change	-17%	-11%	---	+14%

Figure A1-2: EEDI for Oil Tanker Standard Design (Larkin et at, 2010)

Table A1-3: Selected Main Engines for Matrix of Oil Tankers (Larkin et at, 2010)

Main Engine Selection		-2 knots	-1 knots	Standard	+1 knots
Panamax	Service Speed (design)	12.90	13.90	14.90	15.90
	Reqd MCR (kW)	5,685	7,291	9,222	11,361
	MAN B&W ME Model	6S42MC7	7S42MC7	6S50MC-C8	5S60MC-C8
	% De-Rating	87.7%	96.4%	92.6%	95.5%
	RPM	136	136	127	105
	SFC at 75% MCR (g-kWhr)	182.4	182.4	177.3	176.3
Aframax	Service Speed (design)	12.90	13.90	14.90	15.90
	Reqd MCR (kW)	9,564	11,073	13,822	17,378
	MAN B&W ME Model	6S50MC-C8	5S60MC-C8	6S60MC-C8	8S60MC-C8
	% De-Rating	96.0%	93.0%	96.8%	91.3%
	RPM	127	105	105	105
	SFC at 75% MCR (g-kWhr)	177.3	176.3	176.3	176.3
Suezmax	Service Speed (design)	13.20	14.20	15.20	16.20
	Reqd MCR (kW)	11,878	13,940	17,185	21,260
	MAN B&W ME Model	5S60MC-C8	5S70MC-C8	6S70MC-C8	7S70MC-C8
	% De-Rating	99.8%	85.3%	87.6%	92.9%
	RPM	105	91	91	91
	SFC at 75% MCR (g-kWhr)	176.3	176.3	176.3	176.3
VLCC	Service Speed (design)	13.80	14.80	15.80	16.80
	Reqd MCR (kW)	19,165	22,097	26,736	32,376
	MAN B&W ME Model	6S70MC-C8	6S80MC-C8	7S80MC-C8	8S80MC-C8
	% De-Rating	97.7%	88.1%	91.4%	96.8%
	RPM	91	78	78	78
	SFC at 75% MCR (g-kWhr)	176.3	175.3	175.3	175.3

Design Speed for Containerships

A1.8 As shown in Table A1-4 and Figure A1-3, reducing speed by 4 knots reduces the EEDI by 34% to 42%, whereas reducing the speed by 1 knot reduces the EEDI by 19% to 27When assessing the powering requirements, the most suitable MAN B&W engine was selected for each scenario. Consistent with recent practice for containerships, ME series engines were selected. The engine is assumed to be de-rated to the power required to attain the design speed at 15% sea margin with the main engine operating at 90% MCR. The smaller engines associated with the slower service speeds may have higher rpm's. The propulsive coefficient is reduced at the higher rpm which somewhat mitigates the benefits of the lower service speed. Table A1-4 shows the selected main engines, % de-rating, and the associated SFC and RPM values that are applied for this matrix of tanker designs and speeds. Note that the SFC values assume the engine at 75% MCR, burning MDO under ISO conditions. A 3% margin above published SFC figures is included to reflect the anticipated difference between the published values and those shown in the EIAPP Certificates.

Table A1-4: Influence of Service Speed on EEDI for Standard Containership Designs (Larkin et al, 2010)

Design Speed Variation		-4 knots	-2 knots	Standard
1,000 TEU (Feedership)	Service Speed (design)	14.50	16.50	18.50
	DWT at SLL draft (tonnes)	13,960	13,856	13,669
	Main Engine MCR (kW)	4,232	6,090	9,337
	Attained EEDI (*$EEDI_A$*)	14.70	18.37	25.18
	Change vs. Standard Design	-42%	-27%	---
4,500 TEU (Panamax)	Service Speed (design)	20.50	22.50	24.50
	DWT at SLL draft (tonnes)	60,008	59,519	58,817
	Main Engine MCR (kW)	20,484	28,040	38,532
	Attained EEDI (*$EEDI_A$*)	11.31	14.15	17.99
	Change vs. Standard Design	-37%	-21%	---
4,500 TEU (Baby Neo-Panamax)	Service Speed (design)	20.50	22.50	24.50
	DWT at SLL draft (tonnes)	62,079	61,539	60,747
	Main Engine MCR (kW)	21,279	29,575	41,330
	Attained EEDI (*$EEDI_A$*)	11.34	14.39	18.64
	Change vs. Standard Design	-39%	-23%	---
8,000 TEU (Post-Panamax)	Service Speed (design)	21.00	23.00	25.00
	DWT at SLL draft (tonnes)	97,857	97,086	96,068
	Main Engine MCR (kW)	31,982	43,341	57,843
	Attained EEDI (*$EEDI_A$*)	10.53	13.07	16.17
	Change vs. Standard Design	-35%	-19%	---
12,500 TEU Ultra Large)	Service Speed (design)	21.00	23.00	25.00
	DWT at SLL draft (tonnes)	146,238	145,221	143,865
	Main Engine MCR (kW)	42,699	57,202	75,920
	Attained EEDI (*$EEDI_A$*)	9.28	11.40	14.01
	Change vs. Standard Design	-34%	-19%	---

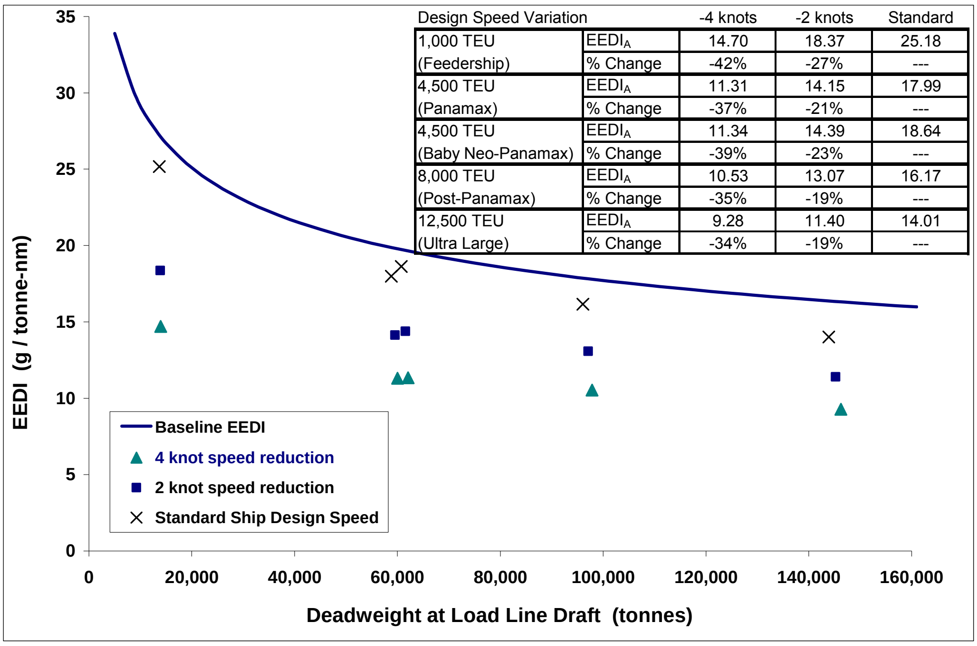


Figure A1-3: EEDI and Speed

Table A1-4: Selected Main Engines for Matrix of Containership Designs (Larkin et al, 2010)

Main Engine Selection		-4 knots	-2 knots	Standard
1,000 TEU (Feedership)	Service Speed (design)	14.50	16.50	18.50
	Reqd MCR (kW)	4,232	6,090	9,337
	MAN B&W ME Model	5S35ME-B9	5S46ME-B8	6S50ME-C8
	% De-Rating	97.3%	88.3%	93.7%
	RPM	167	129	127
	SFC at 75% MCR (g-kWhr)	178.4	175.3	173.3
4,500 TEU (Panamax)	Service Speed (design)	20.50	22.50	24.50
	Reqd MCR (kW)	20,484	28,040	38,532
	MAN B&W ME Model	6K80ME-C6	8K80ME-C6	7K90ME-C9
	% De-Rating	94.6%	97.1%	96.1%
	RPM	104	104	104
	SFC at 75% MCR (g-kWhr)	175.3	175.3	175.3
4,500 TEU (Baby Neo-Panamax)	Service Speed (design)	20.50	22.50	24.50
	Reqd MCR (kW)	21,279	29,575	41,330
	MAN B&W ME Model	6K80ME-C6	7K80ME-C9	7K98ME-C7
	% De-Rating	98.2%	93.3%	98.1%
	RPM	104	104	104
	SFC at 75% MCR (g-kWhr)	175.3	175.3	175.3
8,000 TEU (Post-Panamax)	Service Speed (design)	21.00	23.00	25.00
	Reqd MCR (kW)	31,982	43,341	57,843
	MAN B&W ME Model	9K80ME-C6	10K80ME-C9	10K98ME-C7
	% De-Rating	98.4%	95.7%	96.1%
	RPM	104	104	104
	SFC at 75% MCR (g-kWhr)	175.3	175.3	175.3
12,500 TEU (Ultra Large)	Service Speed (design)	21.00	23.00	25.00
	Reqd MCR (kW)	42,699	57,202	75,920
	MAN B&W ME Model	12K80ME-C6	10K90ME-C9	14K98ME-C7
	% De-Rating	98.6%	99.8%	90.1%
	RPM	104	104	104
	SFC at 75% MCR (g-kWhr)	175.3	175.3	175.3

Capacity

A1-9 Capacity is defined as deadweight for tankers, LNG carriers, and containerships. Capacity for tankers and LNG carriers is taken as the deadweight at the summer load line (SLL) draft. Capacity for containerships is adjusted to be 65% of the SLL deadweight in order to better represent the normal design condition.

Potential to change capacity

A1-10 There have been recent trends, in particular for containerships to increase the TEU capacity as such vessels have been found to be more efficient. Fleet operators are looking to economies of scale. But this does not universally hold among ship types and may not be appropriate depending on the service of the vessel. Geography is a factor. For further information and projections see *Technical support for European action to reducing Greenhouse Gas Emissions from international maritime transport*, (page 262), CE Delft 2009; and Greenhouse gas emissions from shipping: Trends, projections and abatement potential: Final report, pages 80-81. These studies show a projected increasing but gradual trend in ship size. Larkin et al, 2010 estimate that ship designers may be able to decrease EEDI by up to 10% with a virtual increase in capacity and nominal costs which could yield a decreased EEDI, but with no net gain in actual energy efficiency.

Power (P_{ME}, P_{AE}, and P_{PTI})

A1.11 Power from the main engine, P_{ME}, is 75% of the MCR of the engine, in kW, minus the output of any shaft generators (P_{PTO}). Power from auxiliary engines is determined by an empirical formula representing the hotel load and electrical needs for propulsion systems and machinery. Auxiliary power is taken as a function of the MCR of the main engine(s). This formula is adjusted slightly for vessels that have smaller propulsion engines with an installed power less than 10,000 kW. Additional shaft motor inputs P_{PTI} are given at 75% of the rated power consumption divided by the weighted average of the efficiency of the generators.

$$P_{AE(MCRME>10000KW)} = \left(0.025 \times \sum_{i=1}^{nME} MCR_{MEi}\right) + 250$$

$$P_{AE(MCRME<10000KW)} = 0.05 \times \sum_{i=1}^{nME} MCR_{MEi}$$

Potential to reduce main engine power (P_{ME})

A1.12 Reductions in main engine power requirements can result from optimization of hydrodynamic and aerodynamic designs and propulsion configurations (propulsion dynamics and design). Such corresponding changes in power requirements would not necessarily result in the under powering of a vessel. Or as discussed in the design speed section, a reduction in main engine power requirements could result from a reduction in a vessel's design speed.

A1.13 Reduction in main engine power requirements can also result from deliberate decisions by a ship owner or ship builder. There has been concerned raised that this could lead to the under powering of a vessel and in turn reduction in ship safety. The concern about under-powering could be avoided in part by allowing a vessel to operate at a reduced EEDI with a larger main engine (or engines) that are voluntarily de-rated with a proviso that exceeding the engines' ratings would be permissible so as to ensure the vessel is not endangered; such permissible circumstances would be noted as an endorsement on ships' air pollution certificates and occurrences would be documented in ship's logs subject to inspection and control verification.

Potential to reduce auxiliary engine power through innovative energy efficiency technologies (P_{eff}, P_{AEeff}, and f_{eff})

A1.14 Innovative technologies that provide mechanical or electrical power reductions are accounted for with the P_{eff} and P_{AEeff} terms respectively. An availability factor, f_{eff}, is given for each technology to estimate what percent of the time the technology is available during normal "at-sea" conditions. These include:

- Reductions in auxiliary power can result from reduced on board demand (or increased efficiency) from installed: electronics, refrigeration, lighting, air conditioning, machinery, and other equipment.

- Reduction in auxiliary power can result from increased efficiency of generators (and shaft motor efficiencies), switching, and on board power load management.

- Solar power and installed wind-generated power.

- Waste heat recovery from main and auxiliary to power or augment onboard boilers and generators.

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APPENDIX II

ABATEMENT MEASURES

A2.1 In the following tables the costs and the abatement potentials of the different abatement measures are given per ship type.

Table A2-1: Operational speed reduction (-10%)

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	83,932,340	89,124,040	2,669,740	3,263,020	19	19
Crude oil tanker	120-199,999 dwt	56,826,970	60,342,040	2,302,320	2,813,940	19	19
Crude oil tanker	80-119,999 dwt	44,970,690	47,752,390	2,081,860	2,544,500	19	19
Crude oil tanker	60-79,999 dwt	40,005,260	42,479,820	1,971,630	2,409,780	19	19
Crude oil tanker	10-59,999 dwt	34,900,850	37,059,660	1,843,040	2,252,600	19	19
Crude oil tanker	-9,999 dwt	31,047,280	32,967,730	1,732,810	2,117,880	19	19
Product tanker	60,000+ dwt	41,596,290	44,169,260	2,008,380	2,454,680	19	19
Product tanker	20-59,999 dwt	35,588,090	37,789,420	1,861,410	2,275,050	19	19
Product tanker	10-19,999 dwt	31,658,640	33,616,900	1,751,180	2,140,330	19	19
Product tanker	5-9,999 dwt	31,351,470	33,290,730	1,741,990	2,129,100	19	19
Product tanker	-4,999 dwt	30,746,040	32,647,850	1,723,620	2,106,650	19	19
Chemical tanker	20,000+ dwt	34,226,870	36,344,000	1,824,660	2,230,150	19	19
Chemical tanker	10-19,999 dwt	32,282,040	34,278,870	1,769,550	2,162,780	19	19
Chemical tanker	5 -9,999 dwt	31,351,470	33,290,730	1,741,990	2,129,100	19	19
Chemical tanker	-4,999 dwt	30,746,040	32,647,850	1,723,620	2,106,650	19	19
LPG tanker	50,000+ cbm	61,110,000	64,890,000	2,875,500	3,514,500	19	19
LPG tanker	-49,999 cbm	33,950,000	36,050,000	2,236,500	2,733,500	19	19
LNG tanker	200,000+ cbm	162,960,000	173,040,000	2,875,500	3,514,500	19	19
LNG tanker	-199,999 cbm	101,850,000	108,150,000	2,236,500	2,733,500	19	19
Other tanker		31,047,280	32,967,730	1,732,810	2,117,880	19	19
Bulker	200,000+ dwt	145,131,060	154,108,240	1,918,870	2,345,290	19	19
Bulker	100-199,999 dwt	57,970,670	61,556,490	1,744,040	2,131,600	19	19
Bulker	60-99,999 dwt	35,763,840	37,976,030	1,570,920	1,920,010	19	19
Bulker	35-59,999 dwt	28,579,430	30,347,230	1,427,350	1,744,530	19	19
Bulker	10-34,999 dwt	24,051,260	25,538,960	1,221,560	1,493,010	19	19
Bulker	-9,999 dwt	21,315,560	22,634,050	807,320	986,720	19	19
General cargo	10,000+ dwt	25,769,390	27,363,370	1,833,850	2,241,370	19	19
General cargo	5,000-9,999 dwt	21,686,440	23,027,870	918,990	1,123,210	19	19
General cargo	-4,999 dwt	20,951,020	22,246,960	616,420	753,400	19	19

General cargo	10,000+ dwt, 100+ TEU	28,346,330	30,099,710	1,322,830	1,616,790	19	19
General cargo	5,000-9,999 dwt, 100+ TEU	23,855,090	25,330,660	918,990	1,123,210	19	19
General cargo	-4,999 dwt, 100+ TEU	23,046,120	24,471,650	616,420	753,400	19	19
Other dry cargo	Reefer	23,447,110	24,897,450	1,214,100	1,483,900	19	19
Other dry cargo	Special	23,447,110	24,897,450	1,214,420	1,484,290	19	19
Container	8,000+ TEU	79,981,440	84,928,740	3,014,320	3,684,170	19	19
Container	5 -7,999 TEU	64,967,980	68,986,620	2,839,370	3,470,340	19	19
Container	3 -4,999 TEU	54,633,350	58,012,740	2,615,530	3,196,760	19	19
Container	2 -2,999 TEU	49,239,420	52,285,160	2,398,840	2,931,910	19	19
Container	1 -1,999 TEU	45,942,680	48,784,500	2,163,330	2,644,070	19	19
Container	-999 TEU	42,866,670	45,518,220	1,656,820	2,025,010	19	19
Vehicle carrier	4,000+ CEU						
Vehicle carrier	-3,999 CEU						
RoRo	2,000+ lm						
RoRo	-1,999 lm						
Ferry	Pax Only, 25kn+						
Ferry	Pax Only, <25kn						
Ferry	RoPax, 25kn+						
Ferry	RoPax, <25kn						
Cruise vessel	100,000+ GT						
Cruise vessel	60-99,999 GT						
Cruise vessel	10-59,999 GT						
Cruise vessel	2-9,999 GT						
Cruise vessel	-1,999 GT						

Table A2-2: Operational speed reduction (-20%)

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	83,932,340	89,124,040	2,669,740	3,263,020	36	36
Crude oil tanker	120-199,999 dwt	56,826,970	60,342,040	2,302,320	2,813,940	36	36
Crude oil tanker	80-119,999 dwt	44,970,690	47,752,390	2,081,860	2,544,500	36	36
Crude oil tanker	60-79,999 dwt	40,005,260	42,479,820	1,971,630	2,409,780	36	36
Crude oil tanker	10-59,999 dwt	34,900,850	37,059,660	1,843,040	2,252,600	36	36
Crude oil tanker	-9,999 dwt	31,047,280	32,967,730	1,732,810	2,117,880	36	36
Product tanker	60,000+ dwt	41,596,290	44,169,260	2,008,380	2,454,680	36	36
Product tanker	20-59,999 dwt	35,588,090	37,789,420	1,861,410	2,275,050	36	36
Product tanker	10-19,999 dwt	31,658,640	33,616,900	1,751,180	2,140,330	36	36
Product tanker	5-9,999 dwt	31,351,470	33,290,730	1,741,990	2,129,100	36	36
Product tanker	-4,999 dwt	30,746,040	32,647,850	1,723,620	2,106,650	36	36
Chemical tanker	20,000+ dwt	34,226,870	36,344,000	1,824,660	2,230,150	36	36
Chemical tanker	10-19,999 dwt	32,282,040	34,278,870	1,769,550	2,162,780	36	36
Chemical tanker	5 -9,999 dwt	31,351,470	33,290,730	1,741,990	2,129,100	36	36
Chemical tanker	-4,999 dwt	30,746,040	32,647,850	1,723,620	2,106,650	36	36
LPG tanker	50,000+ cbm	61,110,000	64,890,000	2,875,500	3,514,500	36	36
LPG tanker	-49,999 cbm	33,950,000	36,050,000	2,236,500	2,733,500	36	36
LNG tanker	200,000+ cbm	162,960,000	173,040,000	2,875,500	3,514,500	36	36
LNG tanker	-199,999 cbm	101,850,000	108,150,000	2,236,500	2,733,500	36	36
Other tanker		31,047,280	32,967,730	1,732,810	2,117,880	36	36
Bulker	200,000+ dwt	145,131,060	154,108,240	1,918,870	2,345,290	36	36
Bulker	100-199,999 dwt	57,970,670	61,556,490	1,744,040	2,131,600	36	36
Bulker	60-99,999 dwt	35,763,840	37,976,030	1,570,920	1,920,010	36	36
Bulker	35-59,999 dwt	28,579,430	30,347,230	1,427,350	1,744,530	36	36

Bulker	10-34,999 dwt	24,051,260	25,538,960	1,221,560	1,493,010	36	36
Bulker	-9,999 dwt	21,315,560	22,634,050	807,320	986,720	36	36
General cargo	10,000+ dwt	25,769,390	27,363,370	1,833,850	2,241,370	36	36
General cargo	5,000-9,999 dwt	21,686,440	23,027,870	918,990	1,123,210	36	36
General cargo	-4,999 dwt	20,951,020	22,246,960	616,420	753,400	36	36
General cargo	10,000+ dwt, 100+ TEU	28,346,330	30,099,710	1,322,830	1,616,790	36	36
General cargo	5,000-9,999 dwt, 100+ TEU	23,855,090	25,330,660	918,990	1,123,210	36	36
General cargo	-4,999 dwt, 100+ TEU	23,046,120	24,471,650	616,420	753,400	36	36
Other dry cargo	Reefer	23,447,110	24,897,450	1,214,100	1,483,900	36	36
Other dry cargo	Special	23,447,110	24,897,450	1,214,420	1,484,290	36	36
Container	8,000+ TEU	79,981,440	84,928,740	3,014,320	3,684,170	36	36
Container	5 -7,999 TEU	64,967,980	68,986,620	2,839,370	3,470,340	36	36
Container	3 -4,999 TEU	54,633,350	58,012,740	2,615,530	3,196,760	36	36
Container	2 -2,999 TEU	49,239,420	52,285,160	2,398,840	2,931,910	36	36
Container	1 -1,999 TEU	45,942,680	48,784,500	2,163,330	2,644,070	36	36
Container	-999 TEU	42,866,670	45,518,220	1,656,820	2,025,010	36	36
Vehicle carrier	4,000+ CEU						
Vehicle carrier	-3,999 CEU						
RoRo	2,000+ lm						
RoRo	-1,999 lm						
Ferry	Pax Only, 25kn+						
Ferry	Pax Only, <25kn						
Ferry	RoPax, 25kn+						
Ferry	RoPax, <25kn						
Cruise vessel	100,000+ GT						
Cruise vessel	60-99,999 GT						
Cruise vessel	10-59,999 GT						
Cruise vessel	2-9,999 GT						
Cruise vessel	-1,999 GT						

Table A2-3: Weather routing

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt			800	1,600	0.1	4
Crude oil tanker	120-199,999 dwt			800	1,600	0.1	4
Crude oil tanker	80-119,999 dwt			800	1,600	0.1	4
Crude oil tanker	60-79,999 dwt			800	1,600	0.1	4
Crude oil tanker	10-59,999 dwt			800	1,600	0.1	4
Crude oil tanker	-9,999 dwt			800	1,600	0.1	4
Product tanker	60,000+ dwt			800	1,600	0.1	4
Product tanker	20-59,999 dwt			800	1,600	0.1	4
Product tanker	10-19,999 dwt			800	1,600	0.1	4
Product tanker	5-9,999 dwt			800	1,600	0.1	4
Product tanker	-4,999 dwt			800	1,600	0.1	4
Chemical tanker	20,000+ dwt			800	1,600	0.1	4
Chemical tanker	10-19,999 dwt			800	1,600	0.1	4
Chemical tanker	5 -9,999 dwt			800	1,600	0.1	4
Chemical tanker	-4,999 dwt			800	1,600	0.1	4
LPG tanker	50,000+ cbm			800	1,600	0.1	4
LPG tanker	-49,999 cbm			800	1,600	0.1	4
LNG tanker	200,000+ cbm			800	1,600	0.1	4
LNG tanker	-199,999 cbm			800	1,600	0.1	4
Other tanker				800	1,600	0.1	4
Bulker	200,000+ dwt			800	1,600	0.1	4
Bulker	100-199,999 dwt			800	1,600	0.1	4
Bulker	60-99,999 dwt			800	1,600	0.1	4
Bulker	35-59,999 dwt			800	1,600	0.1	4
Bulker	10-34,999 dwt			800	1,600	0.1	4
Bulker	-9,999 dwt			800	1,600	0.1	4
General cargo	10,000+ dwt			800	1,600	0.1	4
General cargo	5,000-9,999 dwt			800	1,600	0.1	4
General cargo	-4,999 dwt			800	1,600	0.1	4
General cargo	10,000+ dwt, 100+ TEU			800	1,600	0.1	4

General cargo	5,000-9,999 dwt, 100+ TEU	800	1,600	0.1	4
General cargo	-4,999 dwt, 100+ TEU	800	1,600	0.1	4
Other dry cargo	Reefer	800	1,600	0.1	4
Other dry cargo	Special	800	1,600	0.1	4
Container	8,000+ TEU	800	1,600	0.1	4
Container	5 -7,999 TEU	800	1,600	0.1	4
Container	3 -4,999 TEU	800	1,600	0.1	4
Container	2 -2,999 TEU	800	1,600	0.1	4
Container	1 -1,999 TEU	800	1,600	0.1	4
Container	-999 TEU	800	1,600	0.1	4
Vehicle carrier	4,000+ CEU	800	1,600	0.1	4
Vehicle carrier	-3,999 CEU	800	1,600	0.1	4
RoRo	2,000+ lm	800	1,600	0.1	4
RoRo	-1,999 lm	800	1,600	0.1	4
Ferry	Pax Only, 25kn+				
Ferry	Pax Only, <25kn				
Ferry	RoPax, 25kn+				
Ferry	RoPax, <25kn				
Cruise vessel	100,000+ GT				
Cruise vessel	60-99,999 GT				
Cruise vessel	10-59,999 GT				
Cruise vessel	2-9,999 GT				
Cruise vessel	-1,999 GT				

Table A2-4: Autopilot adjustment

		Non-recurring costs (2007 US $)		Annual Recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	60,500	66,870			0.5	3
Crude oil tanker	120-199,999 dwt	46,940	51,890			0.5	3
Crude oil tanker	80-119,999 dwt	40,170	44,400			0.5	3
Crude oil tanker	60-79,999 dwt	30,000	33,160			0.5	3
Crude oil tanker	10-59,999 dwt	21,110	23,330			0.5	3
Crude oil tanker	-9,999 dwt	4,540	5,010			0.5	3
Product tanker	60,000+ dwt	30,540	33,750			0.5	3
Product tanker	20-59,999 dwt	20,990	23,200			0.5	3
Product tanker	10-19,999 dwt	13,250	14,640			0.5	3
Product tanker	5-9,999 dwt	7,440	8,230			0.5	3
Product tanker	-4,999 dwt	2,530	2,790			0.5	3
Chemical tanker	20,000+ dwt	23,660	26,150			0.5	3
Chemical tanker	10-19,999 dwt	13,550	14,980			0.5	3
Chemical tanker	5 -9,999 dwt	8,620	9,530			0.5	3
Chemical tanker	-4,999 dwt	2,400	2,650			0.5	3
LPG tanker	50,000+ cbm	33,090	36,570			0.5	3
LPG tanker	-49,999 cbm	5,830	6,440			0.5	3
LNG tanker	200,000+ cbm	80,700	89,200			0.5	3
LNG tanker	-199,999 cbm	84,370	93,250			0.5	3
Other tanker		2,760	3,050			0.5	3
Bulker	200,000+ dwt	40,900	45,210			0.5	3
Bulker	100-199,999 dwt	35,240	38,950			0.5	3
Bulker	60-99,999 dw	23,990	26,520			0.5	3
Bulker	35-59,999 dwt	19,430	21,470			0.5	3
Bulker	10-34,999 dwt	15,310	16,920			0.5	3
Bulker	-9,999 dwt	2,980	3,290			0.5	3
General cargo	10,000+ dwt	15,760	17,420			0.5	3
General cargo	5,000-9,999 dwt	8,630	9,540			0.5	3
General cargo	-4,999 dwt	1,600	1,770			0.5	3
General cargo	10,000+ dwt, 100+ TEU	16,140	17,840			0.5	3
General cargo	5,000-9,999 dwt, 100+ TEU	6,390	7,060			0.5	3
General cargo	-4,999 dwt, 100+ TEU	3,580	3,960			0.5	3
Other dry cargo	Reefer	12,410	13,710			0.5	3

Other dry cargo	Special	11,850	13,090	0.5	3
Container	8,000+ TEU	130,420	144,150	0.5	3
Container	5 -7,999 TEU	105,110	116,170	0.5	3
Container	3 -4,999 TEU	69,840	77,190	0.5	3
Container	2 -2,999 TEU	44,200	48,860	0.5	3
Container	1 -1,999 TEU	27,790	30,710	0.5	3
Container	-999 TEU	9,770	10,800	0.5	3
Vehicle carrier	4,000+ CEU	35,840	39,610	0.5	3
Vehicle carrier	-3,999 CEU	19,960	22,060	0.5	3
RoRo	2,000+ lm	27,900	30,830	0.5	3
RoRo	-1,999 lm	5,160	5,700	0.5	3
Ferry	Pax Only, 25kn+	6,680	7,390	0.5	3
Ferry	Pax Only, <25kn	3,300	3,650	0.5	3
Ferry	RoPax, 25kn+	48,390	53,490	0.5	3
Ferry	RoPax, <25kn	12,940	14,300	0.5	3
Cruise vessel	100,000+ GT	123,540	136,550	0.5	3
Cruise vessel	60-99,999 GT	92,060	101,750	0.5	3
Cruise vessel	10-59,999 GT	36,980	40,870	0.5	3
Cruise vessel	2-9,999 GT	10,420	11,520	0.5	3
Cruise vessel	-1,999 GT	1,850	2,050	0.5	3

Table A2-5: Propeller polishing when required (in the table only the costs for propeller monitoring are given; polishing costs of $3000 - $5000 per polishing per propeller have to be taken into account too)

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	77790	85970			2.5	8
Crude oil tanker	120-199,999 dwt	60360	66710			2.5	8
Crude oil tanker	80-119,999 dwt	51650	57090			2.5	8
Crude oil tanker	60-79,999 dwt	38570	42630			2.5	8
Crude oil tanker	10-59,999 dwt	27140	30000			2.5	8
Crude oil tanker	-9,999 dwt	5830	6450			2.5	8
Product tanker	60,000+ dwt	39260	43400			2.5	8
Product tanker	20-59,999 dwt	26980	29820			2.5	8
Product tanker	10-19,999 dwt	17030	18820			2.5	8
Product tanker	5-9,999 dwt	9570	10580			2.5	8
Product tanker	-4,999 dwt	3250	3590			2.5	8
Chemical tanker	20,000+ dwt	30420	33620			2.5	8
Chemical tanker	10-19,999 dwt	17420	19260			2.5	8
Chemical tanker	5 -9,999 dwt	11080	12250			2.5	8
Chemical tanker	-4,999 dwt	3080	3410			2.5	8
LPG tanker	50,000+ cbm	42540	47020			2.5	8
LPG tanker	-49,999 cbm	7500	8280			2.5	8
LNG tanker	200,000+ cbm	103760	114680			2.5	8
LNG tanker	-199,999 cbm	108470	119890			2.5	8
Other tanker		3550	3930			2.5	8
Bulker	200,000+ dwt	52590	58120			2.5	8
Bulker	100-199,999 dwt	45310	50080			2.5	8
Bulker	60-99,999 dwt	30850	34090			2.5	8
Bulker	35-59,999 dwt	24980	27600			2.5	8
Bulker	10-34,999 dwt	19690	21760			2.5	8
Bulker	-9,999 dwt	3830	4240			2.5	8
General cargo	10,000+ dwt	20260	22390			2.5	8
General cargo	5,000-9,999 dwt	11100	12270			2.5	8
General cargo	-4,999 dwt	2060	2280			2.5	8
General cargo	10,000+ dwt, 100+ TEU	20750	22940			2.5	8
General cargo	5,000-9,999 dwt, 100+	8210	9080			2.5	8

	TEU					
General cargo	-4,999 dwt, 100+ TEU	4600	5090		2.5	8
Other dry cargo	Reefer	15950	17630		2.5	8
Other dry cargo	Special	15230	16830		2.5	8
Container	8,000+ TEU	167690	185340		2.5	8
Container	5 -7,999 TEU	135140	149360		2.5	8
Container	3 -4,999 TEU	89790	99240		2.5	8
Container	2 -2,999 TEU	56830	62820		2.5	8
Container	1 -1,999 TEU	35730	39490		2.5	8
Container	-999 TEU	12560	13880		2.5	8
Vehicle carrier	4,000+ CEU	46070	50920		2.5	8
Vehicle carrier	-3,999 CEU	25660	28360		2.5	8
RoRo	2,000+ lm	35870	39640		2.5	8
RoRo	-1,999 lm	6630	7330		2.5	8
Ferry	Pax Only, 25kn+	8590	9500		2.5	8
Ferry	Pax Only, <25kn	4250	4690		2.5	8
Ferry	RoPax, 25kn+	62220	68770		2.5	8
Ferry	RoPax, <25kn	16640	18390		2.5	8
Cruise vessel	100,000+ GT	158840	175560		2.5	8
Cruise vessel	60-99,999 GT	118360	130820		2.5	8
Cruise vessel	10-59,999 GT	47550	52550		2.5	8
Cruise vessel	2-9,999 GT	13400	14810		2.5	8
Cruise vessel	-1,999 GT	2380	2630		2.5	8

Table A2-6: Hull cleaning

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt					1	10
Crude oil tanker	120-199,999 dwt					1	10
Crude oil tanker	80-119,999 dwt					1	10
Crude oil tanker	60-79,999 dwt					1	10
Crude oil tanker	10-59,999 dwt					1	10
Crude oil tanker	-9,999 dwt					1	10
Product tanker	60,000+ dwt					1	10
Product tanker	20-59,999 dwt					1	10
Product tanker	10-19,999 dwt					1	10
Product tanker	5-9,999 dwt					1	10
Product tanker	-4,999 dwt					1	10
Chemical tanker	20,000+ dwt					1	10
Chemical tanker	10-19,999 dwt					1	10
Chemical tanker	5 -9,999 dwt					1	10
Chemical tanker	-4,999 dwt					1	10
LPG tanker	50,000+ cbm					1	10
LPG tanker	-49,999 cbm					1	10
LNG tanker	200,000+ cbm					1	10
LNG tanker	-199,999 cbm					1	10
Other tanker						1	10
Bulker	200,000+ dwt					1	10
Bulker	100-199,999 dwt					1	10
Bulker	60-99,999 dwt					1	10
Bulker	35-59,999 dwt					1	10
Bulker	10-34,999 dwt					1	10
Bulker	-9,999 dwt					1	10
General cargo	10,000+ dwt					1	10
General cargo	5,000-9,999 dwt					1	10
General cargo	-4,999 dwt					1	10
General cargo	10,000+ dwt, 100+ TEU					1	10
General cargo	5,000-9,999 dwt, 100+ TEU					1	10
General cargo	-4,999 dwt, 100+ TEU					1	10

Other dry cargo	Reefer	1	10
Other dry cargo	Special	1	10
Container	8,000+ TEU	1	10
Container	5 -7,999 TEU	1	10
Container	3 -4,999 TEU	1	10
Container	2 -2,999 TEU	1	10
Container	1 -1,999 TEU	1	10
Container	-999 TEU	1	10
Vehicle carrier	4,000+ CEU	1	10
Vehicle carrier	-3,999 CEU	1	10
RoRo	2,000+ lm	1	10
RoRo	-1,999 lm	1	10
Ferry	Pax Only, 25kn+	1	10
Ferry	Pax Only, <25kn	1	10
Ferry	RoPax, 25kn+	1	10
Ferry	RoPax, <25kn	1	10
Cruise vessel	100,000+ GT	1	10
Cruise vessel	60-99,999 GT	1	10
Cruise vessel	10-59,999 GT	1	10
Cruise vessel	2-9,999 GT	1	10
Cruise vessel	-1,999 GT	1	10

Table A2-7: Hull coating I

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	123,350	146,300			0.5	2
Crude oil tanker	120-199,999 dwt	79,600	94,410			0.5	2
Crude oil tanker	80-119,999 dwt	63,070	74,810			0.5	2
Crude oil tanker	60-79,999 dwt	49,430	58,630			0.5	2
Crude oil tanker	10-59,999 dwt	35,750	42,400			0.5	2
Crude oil tanker	-9,999 dwt	6,960	8,250			0.5	2
Product tanker	60,000+ dwt	55,330	65,630			0.5	2
Product tanker	20-59,999 dwt	35,720	42,370			0.5	2
Product tanker	10-19,999 dwt	19,420	23,030			0.5	2
Product tanker	5-9,999 dwt	11,210	13,290			0.5	2
Product tanker	-4,999 dwt	4,420	5,240			0.5	2
Chemical tanker	20,000+ dwt	36,360	43,130			0.5	2
Chemical tanker	10-19,999 dwt	18,930	22,450			0.5	2
Chemical tanker	5 -9,999 dwt	11,880	14,090			0.5	2
Chemical tanker	-4,999 dwt	5,160	6,120			0.5	2
LPG tanker	50,000+ cbm	52,950	62,800			0.5	2
LPG tanker	-49,999 cbm	12,190	14,450			0.5	2
LNG tanker	200,000+ cbm	112,640	133,590			0.5	2
LNG tanker	-199,999 cbm	86,190	102,230			0.5	2
Other tanker		6,830	8,110			0.5	2
Bulker	200,000+ dwt	100,520	119,220			0.5	2
Bulker	100-199,999 dwt	81,510	96,670			0.5	2
Bulker	60-99,999 dwt	49,490	58,700			0.5	2
Bulker	35-59,999 dwt	38,920	46,170			0.5	2
Bulker	10-34,999 dwt	26,330	31,230			0.5	2
Bulker	-9,999 dwt	6,630	7,870			0.5	2
General cargo	10,000+ dwt	21,570	25,580			0.5	2
General cargo	5,000-9,999 dwt	11,970	14,190			0.5	2

General cargo	-4,999 dwt	4,430	5,260		0.5	2
General cargo	10,000+ dwt, 100+ TEU	26,660	31,620		0.5	2
General cargo	5,000-9,999 dwt, 100+ TEU	12,950	15,360		0.5	2
General cargo	-4,999 dwt, 100+ TEU	8,310	9,860		0.5	2
Other dry cargo	Reefer	12,460	14,780		0.5	2
Other dry cargo	Special	22,590	26,790		0.5	2
Container	8,000+ TEU	91,880	108,970		0.5	2
Container	5 -7,999 TEU	72,600	86,100		0.5	2
Container	3 -4,999 TEU	54,180	64,260		0.5	2
Container	2 -2,999 TEU	40,570	48,120		0.5	2
Container	1 -1,999 TEU	27,560	32,680		0.5	2
Container	-999 TEU	15,550	18,440		0.5	2
Vehicle carrier	4,000+ CEU	59,040	70,020		0.5	2
Vehicle carrier	-3,999 CEU	31,990	37,940		0.5	2
RoRo	2,000+ lm	37,140	44,050		0.5	2
RoRo	-1,999 lm	9,930	11,780		0.5	2
Ferry	Pax Only, 25kn+	1,920	2,280		0.5	2
Ferry	Pax Only, <25kn	2,280	2,710		0.5	2
Ferry	RoPax, 25kn+	22,490	26,670		0.5	2
Ferry	RoPax, <25kn	12,000	14,230		0.5	2
Cruise vessel	100,000+ GT	103,140	122,330		0.5	2
Cruise vessel	60-99,999 GT	78,830	93,500		0.5	2
Cruise vessel	10-59,999 GT	40,750	48,330		0.5	2
Cruise vessel	2-9,999 GT	12,210	14,490		0.5	2
Cruise vessel	-1,999 GT	3,250	3,850		0.5	2

Table A2-8: Hull coating II

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	633,980	760,770			1	5
Crude oil tanker	120-199,999 dwt	409,130	490,960			1	5
Crude oil tanker	80-119,999 dwt	324,160	388,990			1	5
Crude oil tanker	60-79,999 dwt	254,070	304,890			1	5
Crude oil tanker	10-59,999 dwt	183,730	220,480			1	5
Crude oil tanker	-9,999 dwt	35,750	42,900			1	5
Product tanker	60,000+ dwt	284,390	341,270			1	5
Product tanker	20-59,999 dwt	183,590	220,310			1	5
Product tanker	10-19,999 dwt	99,790	119,750			1	5
Product tanker	5-9,999 dwt	57,610	69,130			1	5
Product tanker	-4,999 dwt	22,710	27,260			1	5
Chemical tanker	20,000+ dwt	186,880	224,260			1	5
Chemical tanker	10-19,999 dwt	97,270	116,730			1	5
Chemical tanker	5 -9,999 dwt	61,040	73,250			1	5
Chemical tanker	-4,999 dwt	26,500	31,800			1	5
LPG tanker	50,000+ cbm	272,140	326,560			1	5
LPG tanker	-49,999 cbm	62,630	75,160			1	5
LNG tanker	200,000+ cbm	578,900	694,680			1	5
LNG tanker	-199,999 cbm	442,990	531,580			1	5
Other tanker		35,120	42,150			1	5
Bulker	200,000+ dwt	516,600	619,930			1	5
Bulker	100-199,999 dwt	418,900	502,680			1	5
Bulker	60-99,999 dwt	254,370	305,250			1	5
Bulker	35-59,999 dwt	200,050	240,060			1	5
Bulker	10-34,999 dwt	135,310	162,370			1	5
Bulker	-9,999 dwt	34,100	40,920			1	5
General cargo	10,000+ dwt	110,840	133,010			1	5
General cargo	5,000-9,999 dwt	61,500	73,800			1	5
General cargo	-4,999 dwt	22,780	27,340			1	5
General cargo	10,000+ dwt, 100+ TEU	137,010	164,410			1	5
General cargo	5,000-9,999 dwt, 100+ TEU	66,540	79,850			1	5

General cargo	-4,999 dwt, 100+ TEU	42,730	51,280	1	5
Other dry cargo	Reefer	64,040	76,850	1	5
Other dry cargo	Special	116,100	139,320	1	5
Container	8,000+ TEU	472,220	566,660	1	5
Container	5 -7,999 TEU	373,110	447,730	1	5
Container	3 -4,999 TEU	278,450	334,140	1	5
Container	2 -2,999 TEU	208,500	250,200	1	5
Container	1 -1,999 TEU	141,620	169,950	1	5
Container	-999 TEU	79,910	95,890	1	5
Vehicle carrier	4,000+ CEU	303,430	364,110	1	5
Vehicle carrier	-3,999 CEU	164,410	197,300	1	5
RoRo	2,000+ lm	190,900	229,080	1	5
RoRo	-1,999 lm	51,040	61,250	1	5
Ferry	Pax Only, 25kn+	9,870	11,840	1	5
Ferry	Pax Only, <25kn	11,740	14,080	1	5
Ferry	RoPax, 25kn+	115,580	138,700	1	5
Ferry	RoPax, <25kn	61,670	74,000	1	5
Cruise vessel	100,000+ GT	530,120	636,140	1	5
Cruise vessel	60-99,999 GT	405,170	486,200	1	5
Cruise vessel	10-59,999 GT	209,430	251,310	1	5
Cruise vessel	2-9,999 GT	62,780	75,330	1	5
Cruise vessel	-1,999 GT	16,680	20,010	1	5

Table A2-9: Optimization water flow hull openings

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	103,710	114,630			1	5
Crude oil tanker	120-199,999 dwt	80,480	88,950			1	5
Crude oil tanker	80-119,999 dwt	68,870	76,120			1	5
Crude oil tanker	60-79,999 dwt	51,430	56,840			1	5
Crude oil tanker	10-59,999 dwt	36,190	40,000			1	5
Crude oil tanker	-9,999 dwt	7,780	8,590			1	5
Product tanker	60,000+ dwt	52,350	57,860			1	5
Product tanker	20-59,999 dwt	35,980	39,760			1	5
Product tanker	10-19,999 dwt	22,710	25,100			1	5
Product tanker	5-9,999 dwt	12,760	14,100			1	5
Product tanker	-4,999 dwt	4,330	4,790			1	5
Chemical tanker	20,000+ dwt	40,560	44,830			1	5
Chemical tanker	10-19,999 dwt	23,230	25,670			1	5
Chemical tanker	5 -9,999 dwt	14,780	16,330			1	5
Chemical tanker	-4,999 dwt	4,110	4,540			1	5
LPG tanker	50,000+ cbm	56,720	62,690			1	5
LPG tanker	-49,999 cbm	9,990	11,050			1	5
LNG tanker	200,000+ cbm	138,350	152,910			1	5
LNG tanker	-199,999 cbm	144,630	159,860			1	5
Other tanker		4,740	5,240			1	5
Bulker	200,000+ dwt	70,120	77,500			1	5
Bulker	100-199,999 dwt	60,420	66,780			1	5
Bulker	60-99,999 dwt	41,130	45,460			1	5
Bulker	35-59,999 dwt	33,300	36,810			1	5

Bulker	10-34,999 dwt	26,250	29,010		1	5
Bulker	-9,999 dwt	5,110	5,650		1	5
General cargo	10,000+ dwt	27,010	29,850		1	5
General cargo	5,000-9,999 dwt	14,800	16,350		1	5
General cargo	-4,999 dwt	2,750	3,040		1	5
General cargo	10,000+ dwt, 100+ TEU	27,670	30,580		1	5
General cargo	5,000-9,999 dwt, 100+ TEU	10,950	12,110		1	5
General cargo	-4,999 dwt, 100+ TEU	6,140	6,780		1	5
Other dry cargo	Reefer	21,270	23,510		1	5
Other dry cargo	Special	20,310	22,440		1	5
Container	8,000+ TEU	223,580	247,120		1	5
Container	5 -7,999 TEU	180,180	199,150		1	5
Container	3 -4,999 TEU	119,720	132,320		1	5
Container	2 -2,999 TEU	75,780	83,760		1	5
Container	1 -1,999 TEU	47,640	52,650		1	5
Container	-999 TEU	16,750	18,510		1	5
Vehicle carrier	4,000+ CEU	61,430	67,900		1	5
Vehicle carrier	-3,999 CEU	34,220	37,820		1	5
RoRo	2,000+ lm	47,820	52,850		1	5
RoRo	-1,999 lm	8,840	9,770		1	5
Ferry	Pax Only, 25kn+	11,450	12,660		1	5
Ferry	Pax Only, <25kn	5,660	6,260		1	5
Ferry	RoPax, 25kn+	82,960	91,690		1	5
Ferry	RoPax, <25kn	22,180	24,520		1	5
Cruise vessel	100,000+ GT	211,790	234,080		1	5
Cruise vessel	60-99,999 GT	157,820	174,430		1	5
Cruise vessel	10-59,999 GT	63,400	70,070		1	5
Cruise vessel	2-9,999 GT	17,870	19,750		1	5
Cruise vessel	-1,999 GT	3,180	3,510		1	5

Table 2-10: Air lubrication

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	1,730,560	2,595,850	0.3 – 0.5 tonnes fuel per day, depending on sea conditions		5.0	15.0
Crude oil tanker	120-199,999 dwt	1,171,690	1,757,540			5.0	15.0
Crude oil tanker	80-119,999 dwt	927,230	1,390,850			5.0	15.0
Crude oil tanker	60-79,999 dwt	824,850	1,237,280			5.0	15.0
Crude oil tanker	10-59,999 dwt						
Crude oil tanker	-9,999 dwt						
Product tanker	60,000+ dwt						
Product tanker	20-59,999 dwt						
Product tanker	10-19,999 dwt						
Product tanker	5-9,999 dwt						
Product tanker	-4,999 dwt						
Chemical tanker	20,000+ dwt						
Chemical tanker	10-19,999 dwt						
Chemical tanker	5 -9,999 dwt						
Chemical tanker	-4,999 dwt						
LPG tanker	50,000+ cbm	1,260,000	1,890,000			5.0	15.0
LPG tanker	-49,999 cbm						
LNG tanker	200,000+ cb	3,360,000	5,040,000			5.0	15.0
LNG tanker	-199,999 cbm	2,100,000	3,150,000			5.0	15.0
Other tanker							
Bulker	200,000+ dwt	2,992,390	4,488,590			5.0	15.0
Bulker	100-199,999 dwt	1,195,270	1,792,910			5.0	15.0
Bulker	60-99,999 dwt	737,400	1,106,100			5.0	15.0
Bulker	35-59,999 dwt						
Bulker	10-34,999 dwt						
Bulker	-9,999 dwt						
General cargo	10,000+ dwt						
General cargo	5,000-9,999 dwt						
General cargo	-4,999 dwt						
General cargo	10,000+ dwt, 100+ TEU						
General cargo	5,000-9,999 dwt, 100+ TEU						

General cargo	-4,999 dwt, 100+ TEU					
Other dry cargo	Reefer					
Other dry cargo	Special					
Container	8,000+ TEU	1,649,100	2,473,650		2.5	9.0
Container	5 -7,999 TEU	1,339,550	2,009,320		2.5	9.0
Container	3 -4,999 TEU	1,126,460	1,689,690		2.5	9.0
Container	2 -2,999 TEU	1,015,250	1,522,870		2.5	9.0
Container	1 -1,999 TEU					
Container	-999 TEU					
Vehicle carrier	4,000+ CEU					
Vehicle carrier	-3,999 CEU					
RoRo	2,000+ lm					
RoRo	-1,999 lm					
Ferry	Pax Only, 25kn+					
Ferry	Pax Only, <25kn					
Ferry	RoPax, 25kn+					
Ferry	RoPax, <25kn					
Cruise vessel	100,000+ GT					
Cruise vessel	60-99,999 GT					
Cruise vessel	10-59,999 GT					
Cruise vessel	2-9,999 GT					
Cruise vessel	-1,999 GT					

Table A2-12: Integrated propeller and rudder upgrade

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	2,765,720	3,056,850			2	6
Crude oil tanker	120-199,999 dwt	2,146,010	2,371,910			2	6
Crude oil tanker	80-119,999 dwt	1,836,550	2,029,870			2	6
Crude oil tanker	60-79,999 dwt	1,371,470	1,515,830			2	6
Crude oil tanker	10-59,999 dwt	965,130	1,066,720			2	6
Crude oil tanker	-9,999 dwt	207,330	229,160			2	6
Product tanker	60,000+ dwt	1,396,080	1,543,030			2	6
Product tanker	20-59,999 dwt	959,390	1,060,380			2	6
Product tanker	10-19,999 dwt	605,560	669,300			2	6
Product tanker	5-9,999 dwt	340,290	376,110			2	6
Product tanker	-4,999 dwt	115,530	127,690			2	6
Chemical tanker	20,000+ dwt	1,081,630	1,195,490			2	6
Chemical tanker	10-19,999 dwt	619,440	684,640			2	6
Chemical tanker	5 -9,999 dwt	394,020	435,500			2	6
Chemical tanker	-4,999 dwt	109,620	121,160			2	6
LPG tanker	50,000+ cbm	1,512,480	1,671,690			2	6
LPG tanker	-49,999 cbm	266,510	294,560			2	6
LNG tanker	200,000+ cbm	3,689,290	4,077,630			2	6
LNG tanker	-199,999 cbm	3,856,830	4,262,810			2	6
Other tanker		126,350	139,650			2	6
Bulker	200,000+ dwt	1,869,770	2,066,590			2	6
Bulker	100-199,999 dwt	1,611,100	1,780,690			2	6
Bulker	60-99,999 dwt	1,096,770	1,212,210			2	6
Bulker	35-59,999 dwt	888,010	981,490			2	6
Bulker	10-34,999 dwt	699,990	773,680			2	6
Bulker	-9,999 dwt	136,250	150,590			2	6
General cargo	10,000+ dwt	720,310	796,130			2	6
General cargo	5,000-9,999 dwt	394,590	436,130			2	6
General cargo	-4,999 dwt	73,280	80,990			2	6
General cargo	10,000+ dwt, 100+ TEU	737,810	815,480			2	6
General cargo	5,000-9,999 dwt, 100+ TEU	292,080	322,830			2	6
General cargo	-4,999 dwt, 100+ TEU	163,690	180,920			2	6

Other dry cargo	Reefer	567,180	626,890		2	6
Other dry cargo	Special	541,520	598,530		2	6
Container	8,000+ TEU	5,962,150	6,589,740		2	6
Container	5 -7,999 TEU	4,804,920	5,310,700		2	6
Container	3 -4,999 TEU	3,192,550	3,528,600		2	6
Container	2 -2,999 TEU	2,020,760	2,233,470		2	6
Container	1 -1,999 TEU	1,270,360	1,404,090		2	6
Container	-999 TEU	446,580	493,590		2	6
Vehicle carrier	4,000+ CEU	1,638,200	1,810,640		2	6
Vehicle carrier	-3,999 CEU	912,440	1,008,480		2	6
RoRo	2,000+ lm	1,275,220	1,409,450		2	6
RoRo	-1,999 lm	235,710	260,530		2	6
Ferry	Pax Only, 25kn+					
Ferry	Pax Only, <25kn					
Ferry	RoPax, 25kn+					
Ferry	RoPax, <25kn					
Cruise vessel	100,000+ GT					
Cruise vessel	60-99,999 GT					
Cruise vessel	10-59,999 GT					
Cruise vessel	2-9,999 GT					
Cruise vessel	-1,999 GT					

Table A2-13: Propeller upgrade

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	1,728,580	1,910,530			0.5	4.5
Crude oil tanker	120-199,999 dwt	1,341,260	1,482,440			0.5	4.5
Crude oil tanker	80-119,999 dwt	1,147,840	1,268,670			0.5	4.5
Crude oil tanker	60-79,999 dwt	857,170	947,400			0.5	4.5
Crude oil tanker	10-59,999 dwt	603,210	666,700			0.5	4.5
Crude oil tanker	-9,999 dwt	129,580	143,220			0.5	4.5
Product tanker	60,000+ dwt	872,550	964,400			0.5	4.5
Product tanker	20-59,999 dwt	599,620	662,730			0.5	4.5
Product tanker	10-19,999 dwt	378,470	418,310			0.5	4.5
Product tanker	5-9,999 dwt	212,680	235,070			0.5	4.5
Product tanker	-4,999 dwt	72,210	79,810			0.5	4.5
Chemical tanker	20,000+ dwt	676,020	747,180			0.5	4.5
Chemical tanker	10-19,999 dwt	387,150	427,900			0.5	4.5
Chemical tanker	5 -9,999 dwt	246,260	272,190			0.5	4.5
Chemical tanker	-4,999 dwt	68,510	75,730			0.5	4.5
LPG tanker	50,000+ cbm	945,300	1,044,810			0.5	4.5
LPG tanker	-49,999 cbm	166,570	184,100			0.5	4.5
LNG tanker	200,000+ cbm	2,305,810	2,548,520			0.5	4.5
LNG tanker	-199,999 cbm	2,410,520	2,664,260			0.5	4.5
Other tanker		78,970	87,280			0.5	4.5
Bulker	200,000+ dwt						
Bulker	100-199,999 dwt						
Bulker	60-99,999 dwt						
Bulker	35-59,999 dwt						
Bulker	10-34,999 dwt						
Bulker	-9,999 dwt						
General cargo	10,000+ dwt						
General cargo	5,000-9,999 dwt						
General cargo	-4,999 dwt						
General cargo	10,000+ dwt, 100+ TEU						
General cargo	5,000-9,999 dwt, 100+ TEU						

General cargo	-4,999 dwt, 100+ TEU
Other dry cargo	Reefer
Other dry cargo	Special
Container	8,000+ TEU
Container	5 -7,999 TEU
Container	3 -4,999 TEU
Container	2 -2,999 TEU
Container	1 -1,999 TEU
Container	-999 TEU
Vehicle carrier	4,000+ CEU
Vehicle carrier	-3,999 CEU
RoRo	2,000+ lm
RoRo	-1,999 lm
Ferry	Pax Only, 25kn+
Ferry	Pax Only, <25kn
Ferry	RoPax, 25kn+
Ferry	RoPax, <25kn
Cruise vessel	100,000+ GT
Cruise vessel	60-99,999 GT
Cruise vessel	10-59,999 GT
Cruise vessel	2-9,999 GT
Cruise vessel	-1,999 GT

Table A2-14: Propeller boss cap with fins

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	145,020	177,240			1	3
Crude oil tanker	120-199,999 dwt	104,930	128,250			1	3
Crude oil tanker	80-119,999 dwt	81,800	99,970			1	3
Crude oil tanker	60-79,999 dwt	70,110	85,680			1	3
Crude oil tanker	10-59,999 dwt	56,060	68,520			1	3
Crude oil tanker	-9,999 dwt	24,010	29,350			1	3
Product tanker	60,000+ dwt	81,360	99,440			1	3
Product tanker	20-59,999 dwt	59,210	72,370			1	3
Product tanker	10-19,999 dwt	38,780	47,390			1	3
Product tanker	5-9,999 dwt	28,410	34,720			1	3
Product tanker	-4,999 dwt	19,580	23,930			1	3
Chemical tanker	20,000+ dwt	62,120	75,920			1	3
Chemical tanker	10-19,999 dwt	41,550	50,780			1	3
Chemical tanker	5 -9,999 dwt	31,390	38,370			1	3
Chemical tanker	-4,999 dwt	20,780	25,390			1	3
LPG tanker	50,000+ cbm	85,880	104,960			1	3
LPG tanker	-49,999 cbm	31,250	38,190			1	3
LNG tanker	200,000+ cbm	212,650	259,910			1	3
LNG tanker	-199,999 cbm	144,920	177,130			1	3
Other tanker		22,190	27,120			1	3
Bulker	200,000+ dwt	105,720	129,220			1	3
Bulker	100-199,999 dwt	94,460	115,460			1	3
Bulker	60-99,999 dwt	66,820	81,670			1	3
Bulker	35-59,999 dwt	57,770	70,600			1	3
Bulker	10-34,999 dwt	48,330	59,070			1	3
Bulker	-9,999 dwt	22,240	27,180			1	3
General cargo	10,000+ dwt	45,550	55,680			1	3
General cargo	5,000-9,999 dwt	29,730	36,330			1	3
General cargo	-4,999 dwt	18,710	22,870			1	3
General cargo	10,000+ dwt, 100+ TEU	56,020	68,470			1	3

General cargo	5,000-9,999 dwt, 100+ TEU	33,880	41,410	1	3
General cargo	-4,999 dwt, 100+ TEU	23,990	29,320	1	3
Other dry cargo	Reefer	40,380	49,350	1	3
Other dry cargo	Special	44,880	54,850	1	3
Container	8,000+ TEU	378,400	462,490	1	3
Container	5 -7,999 TEU	310,330	379,290	1	3
Container	3 -4,999 TEU	199,950	244,380	1	3
Container	2 -2,999 TEU	128,270	156,780	1	3
Container	1 -1,999 TEU	79,870	97,620	1	3
Container	-999 TEU	44,430	54,300	1	3
Vehicle carrier	4,000+ CEU	83,980	102,640	1	3
Vehicle carrier	-3,999 CEU	56,500	69,050	1	3
RoRo	2,000+ lm	97,810	119,540	1	3
RoRo	-1,999 lm	29,700	36,300	1	3
Ferry	Pax Only, 25kn+	30,650	37,460	1	3
Ferry	Pax Only, <25kn	20,540	25,110	1	3
Ferry	RoPax, 25kn+	159,830	195,350	1	3
Ferry	RoPax, <25kn	40,110	49,020	1	3
Cruise vessel	100,000+ GT	368,010	449,790	1	3
Cruise vessel	60-99,999 GT	278,920	340,910	1	3
Cruise vessel	10-59,999 GT	115,430	141,080	1	3
Cruise vessel	2-9,999 GT	35,510	43,400	1	3
Cruise vessel	-1,999 GT	19,110	23,360	1	3

Table A2-15: Common rail technology

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	103,710	114,630			0.1	0.5
Crude oil tanker	120-199,999 dwt	80,480	88,950			0.1	0.5
Crude oil tanker	80-119,999 dwt	68,870	76,120			0.1	0.5
Crude oil tanker	60-79,999 dwt	51,430	56,840			0.1	0.5
Crude oil tanker	10-59,999 dwt	36,190	40,000			0.1	0.5
Crude oil tanker	-9,999 dwt	7,780	8,590			0.1	0.5
Product tanker	60,000+ dwt	52,350	57,860			0.1	0.5
Product tanker	20-59,999 dwt	35,980	39,760			0.1	0.5
Product tanker	10-19,999 dwt	22,710	25,100			0.1	0.5
Product tanker	5-9,999 dwt	12,760	14,100			0.1	0.5
Product tanker	-4,999 dwt	4,330	4,790			0.1	0.5
Chemical tanker	20,000+ dwt	40,560	44,830			0.1	0.5
Chemical tanker	10-19,999 dwt	23,230	25,670			0.1	0.5
Chemical tanker	5 -9,999 dwt	14,780	16,330			0.1	0.5
Chemical tanker	-4,999 dwt	4,110	4,540			0.1	0.5
LPG tanker	50,000+ cbm	56,720	62,690			0.1	0.5
LPG tanker	-49,999 cbm	9,990	11,050			0.1	0.5
LNG tanker	200,000+ cbm	138,350	152,910			0.1	0.5
LNG tanker	-199,999 cbm	144,630	159,860			0.1	0.5
Other tanker		4,740	5,240			0.1	0.5
Bulker	200,000+ dwt	70,120	77,500			0.1	0.5
Bulker	100-199,999 dwt	60,420	66,780			0.1	0.5
Bulker	60-99,999 dwt	41,130	45,460			0.1	0.5
Bulker	35-59,999 dwt	33,300	36,810			0.1	0.5
Bulker	10-34,999 dwt	26,250	29,010			0.1	0.5
Bulker	-9,999 dwt	5,110	5,650			0.1	0.5
General cargo	10,000+ dwt	27,010	29,850			0.1	0.5
General cargo	5,000-9,999 dwt	14,800	16,350			0.1	0.5
General cargo	-4,999 dwt	2,750	3,040			0.1	0.5
General cargo	10,000+ dwt, 100+ TEU	27,670	30,580			0.1	0.5
General cargo	5,000-9,999 dwt, 100+ TEU	10,950	12,110			0.1	0.5
General cargo	-4,999 dwt, 100+ TEU	6,140	6,780			0.1	0.5

Other dry cargo	Reefer	21,270	23,510		0.1	0.5
Other dry cargo	Special	20,310	22,440		0.1	0.5
Container	8,000+ TEU	223,580	247,120		0.1	0.5
Container	5 -7,999 TEU	180,180	199,150		0.1	0.5
Container	3 -4,999 TEU	119,720	132,320		0.1	0.5
Container	2 -2,999 TEU	75,780	83,760		0.1	0.5
Container	1 -1,999 TEU	47,640	52,650		0.1	0.5
Container	-999 TEU	16,750	18,510		0.1	0.5
Vehicle carrier	4,000+ CEU	61,430	67,900		0.1	0.5
Vehicle carrier	-3,999 CEU	34,220	37,820		0.1	0.5
RoRo	2,000+ lm	47,820	52,850		0.1	0.5
RoRo	-1,999 lm	8,840	9,770		0.1	0.5
Ferry	Pax Only, 25kn+	11,450	12,660		0.1	0.5
Ferry	Pax Only, <25kn	5,660	6,260		0.1	0.5
Ferry	RoPax, 25kn+	82,960	91,690		0.1	0.5
Ferry	RoPax, <25kn	22,180	24,520		0.1	0.5
Cruise vessel	100,000+ GT	211,790	234,080		0.1	0.5
Cruise vessel	60-99,999 GT	157,820	174,430		0.1	0.5
Cruise vessel	10-59,999 GT	63,400	70,070		0.1	0.5
Cruise vessel	2-9,999 GT	17,870	19,750		0.1	0.5
Cruise vessel	-1,999 GT	3,180	3,510		0.1	0.5

Table A2-16: Main Engine Tuning

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	311,144	343,896			0.1	0.8
Crude oil tanker	120-199,999 dwt	241,427	266,840			0.1	0.8
Crude oil tanker	80-119,999 dwt	206,612	228,360			0.1	0.8
Crude oil tanker	60-79,999 dwt	154,290	170,513			0.1	0.8
Crude oil tanker	10-59,999 dwt	108577	120006			0.1	0.8
Crude oil tanker	-9,999 dwt	23325	25780			0.1	0.8
Product tanker	60,000+ dwt	157,059	173,591			0.1	0.8
Product tanker	20-59,999 dwt	107931	119292			0.1	0.8
Product tanker	10-19,999 dwt	68125	75296			0.1	0.8
Product tanker	5-9,999 dwt	38283	42312			0.1	0.8
Product tanker	-4,999 dwt	12997	14365			0.1	0.8
Chemical tanker	20,000+ dwt	121684	134492			0.1	0.8
Chemical tanker	10-19,999 dwt	69687	77022			0.1	0.8
Chemical tanker	5 -9,999 dwt	44327	48993			0.1	0.8
Chemical tanker	-4,999 dwt	12333	13631			0.1	0.8
LPG tanker	50,000+ cbm	170155	188066			0.1	0.8
LPG tanker	-49,999 cbm	29982	33138			0.1	0.8
LNG tanker	200,000+ cbm	415054	458734			0.1	0.8
LNG tanker	-199,999 cbm	433893	479566			0.1	0.8
Other tanker		14241	15710			0.1	0.8
Bulker	200,000+ dwt	210,349	232,491			0.1	0.8
Bulker	100-199,999 dwt	181,294	200,328			0.1	0.8
Bulker	60-99,999 dwt	123,386	136,374			0.1	0.8
Bulker	35-59,999 dwt	99901	110417			0.1	0.8
Bulker	10-34,999 dwt	78749	87039			0.1	0.8
Bulker	-9,999 dwt	15328	16942			0.1	0.8
General cargo	10,000+ dwt	81034	89564			0.1	0.8
General cargo	5,000-9,999 dwt	44391	49064			0.1	0.8
General cargo	-4,999 dwt	8244	9112			0.1	0.8
General cargo	10,000+ dwt, 100+ TEU	83004	91741			0.1	0.8
General cargo	5,000-9,999 dwt, 100+ TEU	32859	36318			0.1	0.8

General cargo	-4,999 dwt, 100+ TEU	18415	20354	0.1	0.8
Other dry cargo	Reefer	63808	70525	0.1	0.8
Other dry cargo	Special	60921	67334	0.1	0.8
Container	8,000+ TEU	670742	741346	0.1	0.8
Container	5 -7,999 TEU	540554	597454	0.1	0.8
Container	3 -4,999 TEU	359162	396968	0.1	0.8
Container	2 -2,999 TEU	227335	251226	0.1	0.8
Container	1 -1,999 TEU	142916	157960	0.1	0.8
Container	-999 TEU	50241	55529	0.1	0.8
Vehicle carrier	4,000+ CEU	184297	203697	0.1	0.8
Vehicle carrier	-3,999 CEU	102649	113454	0.1	0.8
RoRo	2,000+ lm	143462	158563	0.1	0.8
RoRo	-1,999 lm	26518	29309	0.1	0.8
Ferry	Pax Only, 25kn+				
Ferry	Pax Only, <25kn				
Ferry	RoPax, 25kn+				
Ferry	RoPax, <25kn				
Cruise vessel	100,000+ GT				
Cruise vessel	60-99,999 GT				
Cruise vessel	10-59,999 GT				
Cruise vessel	2-9,999 GT				
Cruise vessel	-1,999 GT				

Table A2-17: Waste heat recovery

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	4,204,510	4,647,100			6	8
Crude oil tanker	120-199,999 dwt	3,336,920	3,688,180			6	8
Crude oil tanker	80-119,999 dwt						
Crude oil tanker	60-79,999 dwt						
Crude oil tanker	10-59,999 dwt						
Crude oil tanker	-9,999 dwt						
Product tanker	60,000+ dwt						
Product tanker	20-59,999 dwt						
Product tanker	10-19,999 dwt						
Product tanker	5-9,999 dwt						
Product tanker	-4,999 dwt						
Chemical tanker	20,000+ dwt						
Chemical tanker	10-19,999 dwt						
Chemical tanker	5 -9,999 dwt						
Chemical tanker	-4,999 dwt						
LPG tanker	50,000+ cbm						
LPG tanker	-49,999 cbm						
LNG tanker	200,000+ cbm	5,497,500	6,076,190			6	8
LNG tanker	-199,999 cbm	5,732,060	6,335,430			6	8
Other tanker							
Bulker	200,000+ dwt						
Bulker	100-199,999 dwt						
Bulker	60-99,999 dwt						
Bulker	35-59,999 dwt						
Bulker	10-34,999 dwt						
Bulker	-9,999 dwt						
General cargo	10,000+ dwt						
General cargo	5,000-9,999 dwt						
General cargo	-4,999 dwt						
General cargo	10,000+ dwt, 100+ TEU						
General cargo	5,000-9,999 dwt, 100+ TEU						
General cargo	-4,999 dwt, 100+ TEU						

Other dry cargo	Reefer				
Other dry cargo	Special				
Container	8,000+ TEU	8,679,510	9,593,140	6	8
Container	5 -7,999 TEU	7,059,390	7,802,480	6	8
Container	3 -4,999 TEU	4,802,070	5,307,550	6	8
Container	2 -2,999 TEU	3,161,560	3,494,360	6	8
Container	1 -1,999 TEU				
Container	-999 TEU				
Vehicle carrier	4,000+ CEU				
Vehicle carrier	-3,999 CEU				
RoRo	2,000+ lm	2,117,800	2,340,730	6	8
RoRo	-1,999 lm				
Ferry	Pax Only, 25kn+				
Ferry	Pax Only, <25kn				
Ferry	RoPax, 25kn+				
Ferry	RoPax, <25kn				
Cruise vessel	100,000+ GT	8,239,200	9,106,480	6	8
Cruise vessel	60-99,999 GT	6,224,320	6,879,510	6	8
Cruise vessel	10-59,999 GT	2,699,310	2,983,450	6	8
Cruise vessel	2-9,999 GT				
Cruise vessel	-1,999 GT				

Table A2-18: Towing kites

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	3,683,220	3,683,220	445,410	513,940	8.5	17.0
Crude oil tanker	120-199,999 dwt	2,784,510	2,784,510	284,930	336,730	5.4	10.9
Crude oil tanker	80-119,999 dwt	2,784,510	2,784,510	284,930	336,730	6.3	12.5
Crude oil tanker	60-79,999 dwt	1,885,810	1,885,810	157,880	192,970	4.0	8.1
Crude oil tanker	10-59,999 dwt	987,100	987,100	64,280	82,640	2.9	5.7
Crude oil tanker	-9,999 dwt	515,650	515,650	23,980	33,580	5.3	10.6
Product tanker	60,000+ dwt	1,885,810	1,885,810	157,880	192,970	2.7	5.4
Product tanker	20-59,999 dwt	987,100	987,100	64,280	82,640	2.1	4.1
Product tanker	10-19,999 dwt	987,100	987,100	64,280	82,640	3.7	7.3
Product tanker	5-9,999 dwt	515,650	515,650	23,980	33,580	3.2	6.3
Product tanker	-4,999 dwt	515,650	515,650	23,980	33,580	9.2	18.4
Chemical tanker	20,000+ dwt	1,885,810	1,885,810	157,880	192,970	5.4	10.8
Chemical tanker	10-19,999 dwt	987,100	987,100	64,280	82,640	4.6	9.2
Chemical tanker	5 -9,999 dwt	515,650	515,650	23,980	33,580	3.8	7.6
Chemical tanker	-4,999 dwt	515,650	515,650	23,980	33,580	10.0	20.0
LPG tanker	50,000+ cbm	1,885,810	1,885,810	157,880	192,970	4.2	8.4
LPG tanker	-49,999 cbm	987,100	987,100	64,280	82,640	8.2	16.4
LNG tanker	200,000+ cbm	2,784,510	2,784,510	284,930	336,730	2.9	5.7
LNG tanker	-199,999 cbm	1,885,810	1,885,810	157,880	192,970	2.3	4.6
Other tanker		515,650	515,650	23,980	33,580	8.7	17.3
Bulker	200,000+ dwt	3,683,220	3,683,220	445,410	513,940	12.9	25.8
Bulker	100-199,999 dwt	2,784,510	2,784,510	284,930	336,730	7.4	14.9
Bulker	60-99,999 dwt	1,885,810	1,885,810	157,880	192,970	5.7	11.4
Bulker	35-59,999 dwt	987,100	987,100	64,280	82,640	3.4	6.8
Bulker	10-34,999 dwt	987,100	987,100	64,280	82,640	4.3	8.5
Bulker	-9,999 dwt	515,650	515,650	23,980	33,580	8.0	16.1
General cargo	10,000+ dwt						
General cargo	5,000-9,999 dwt						
General cargo	-4,999 dwt						
General cargo	10,000+ dwt, 100+ TEU						
General cargo	5,000-9,999 dwt, 100+ TEU						

General cargo	-4,999 dwt, 100+ TEU
Other dry cargo	Reefer
Other dry cargo	Special
Container	8,000+ TEU
Container	5 -7,999 TEU
Container	3 -4,999 TEU
Container	2 -2,999 TEU
Container	1 -1,999 TEU
Container	-999 TEU
Vehicle carrier	4,000+ CEU
Vehicle carrier	-3,999 CEU
RoRo	2,000+ lm
RoRo	-1,999 lm
Ferry	Pax Only, 25kn+
Ferry	Pax Only, <25kn
Ferry	RoPax, 25kn+
Ferry	RoPax, <25kn
Cruise vessel	100,000+ GT
Cruise vessel	60-99,999 GT
Cruise vessel	10-59,999 GT
Cruise vessel	2-9,999 GT
Cruise vessel	-1,999 GT

Table A2-19: Wind engines

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	720,000	900,000			3.6	3.6
Crude oil tanker	120-199,999 dwt	720,000	900,000			4.5	4.5
Crude oil tanker	80-119,999 dwt	720,000	900,000			5.2	5.2
Crude oil tanker	60-79,999 dwt	720,000	900,000			6.6	6.6
Crude oil tanker	10-59,999 dwt						
Crude oil tanker	-9,999 dwt						
Product tanker	60,000+ dwt	720,000	900,000			4.4	4.4
Product tanker	20-59,999 dwt						
Product tanker	10-19,999 dwt						
Product tanker	5-9,999 dwt						
Product tanker	-4,999 dwt						
Chemical tanker	20,000+ dwt						
Chemical tanker	10-19,999 dwt						
Chemical tanker	5 -9,999 dwt						
Chemical tanker	-4,999 dwt						
LPG tanker	50,000+ cbm						
LPG tanker	-49,999 cbm						
LNG tanker	200,000+ cbm						
LNG tanker	-199,999 cbm						
Other tanker							
Bulker	200,000+ dwt	960,000	1,200,000			7.2	7.2
Bulker	100-199,999 dwt	960,000	1,200,000			8.3	8.3
Bulker	60-99,999 dwt	960,000	1,200,000			12.4	12.4
Bulker	35-59,999 dwt						
Bulker	10-34,999 dwt						
Bulker	-9,999 dwt						
General cargo	10,000+ dwt						
General cargo	5,000-9,999 dwt						
General cargo	-4,999 dwt						
General cargo	10,000+ dwt, 100+ TEU						

General cargo	5,000-9,999 dwt, 100+ TEU
General cargo	-4,999 dwt, 100+ TEU
Other dry cargo	Reefer
Other dry cargo	Special
Container	8,000+ TEU
Container	5 -7,999 TEU
Container	3 -4,999 TEU
Container	2 -2,999 TEU
Container	1 -1,999 TEU
Container	-999 TEU
Vehicle carrier	4,000+ CEU
Vehicle carrier	-3,999 CEU
RoRo	2,000+ lm
RoRo	-1,999 lm
Ferry	Pax Only, 25kn+
Ferry	Pax Only, <25kn
Ferry	RoPax, 25kn+
Ferry	RoPax, <25kn
Cruise vessel	100,000+ GT
Cruise vessel	60-99,999 GT
Cruise vessel	10-59,999 GT
Cruise vessel	2-9,999 GT
Cruise vessel	-1,999 GT

Table A2-20: Solar energy

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	1,330,000	1,330,000			0.2	0.2
Crude oil tanker	120-199,999 dwt	1,330,000	1,330,000			0.3	0.3
Crude oil tanker	80-119,999 dwt	1,330,000	1,330,000			0.3	0.3
Crude oil tanker	60-79,999 dwt	1,330,000	1,330,000			0.4	0.4
Crude oil tanker	10-59,999 dwt	1,330,000	1,330,000			0.5	0.5
Crude oil tanker	-9,999 dwt	1,330,000	1,330,000			2.0	2.0
Product tanker	60,000+ dwt	1,330,000	1,330,000			0.3	0.3
Product tanker	20-59,999 dwt	1,330,000	1,330,000			0.4	0.4
Product tanker	10-19,999 dwt	1,330,000	1,330,000			0.7	0.7
Product tanker	5-9,999 dwt	1,330,000	1,330,000			1.2	1.2
Product tanker	-4,999 dwt	1,330,000	1,330,000			3.5	3.5
Chemical tanker	20,000+ dwt	1,330,000	1,330,000			0.5	0.5
Chemical tanker	10-19,999 dwt	1,330,000	1,330,000			0.9	0.9
Chemical tanker	5 -9,999 dwt	1,330,000	1,330,000			1.4	1.4
Chemical tanker	-4,999 dwt	1,330,000	1,330,000			3.7	3.7
LPG tanker	50,000+ cbm	1,330,000	1,330,000			0.4	0.4
LPG tanker	-49,999 cbm	1,330,000	1,330,000			1.5	1.5
LNG tanker	200,000+ cbm	1,330,000	1,330,000			0.1	0.1
LNG tanker	-199,999 cbm	1,330,000	1,330,000			0.2	0.2
Other tanker		1,330,000	1,330,000			3.3	3.3
Bulker	200,000+ dwt						
Bulker	100-199,999 dwt						
Bulker	60-99,999 dwt						
Bulker	35-59,999 dwt						
Bulker	10-34,999 dwt						
Bulker	-9,999 dwt						
General cargo	10,000+ dwt						
General cargo	5,000-9,999 dwt						
General cargo	-4,999 dwt						
General cargo	10,000+ dwt, 100+ TEU						
General cargo	5,000-9,999 dwt, 100+ TEU						
General cargo	-4,999 dwt, 100+ TEU						

Other dry cargo	Reefer					
Other dry cargo	Special					
Container	8,000+ TEU					
Container	5 -7,999 TEU					
Container	3 -4,999 TEU					
Container	2 -2,999 TEU					
Container	1 -1,999 TEU					
Container	-999 TEU					
Vehicle carrier	4,000+ CEU	1,330,000	1,330,000		0.4	0.4
Vehicle carrier	-3,999 CEU	1,330,000	1,330,000		0.6	0.6
RoRo	2,000+ lm	1,330,000	1,330,000		0.4	0.4
RoRo	-1,999 lm	1,330,000	1,330,000		1.7	1.7
Ferry	Pax Only, 25kn+					
Ferry	Pax Only, <25kn					
Ferry	RoPax, 25kn+					
Ferry	RoPax, <25kn					
Cruise vessel	100,000+ GT					
Cruise vessel	60-99,999 GT					
Cruise vessel	10-59,999 GT					
Cruise vessel	2-9,999 GT					
Cruise vessel	-1,999 GT					

Table A2-21: Low energy/low heating lighting

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt						
Crude oil tanker	120-199,999 dwt						
Crude oil tanker	80-119,999 dwt						
Crude oil tanker	60-79,999 dwt						
Crude oil tanker	10-59,999 dwt						
Crude oil tanker	-9,999 dwt						
Product tanker	60,000+ dwt						
Product tanker	20-59,999 dwt						
Product tanker	10-19,999 dwt						
Product tanker	5-9,999 dwt						
Product tanker	-4,999 dwt						
Chemical tanker	20,000+ dwt						
Chemical tanker	10-19,999 dwt						
Chemical tanker	5 -9,999 dwt						
Chemical tanker	-4,999 dwt						
LPG tanker	50,000+ cbm						
LPG tanker	-49,999 cbm						
LNG tanker	200,000+ cbm						
LNG tanker	-199,999 cbm						
Other tanker							
Bulker	200,000+ dwt						
Bulker	100-199,999 dwt						
Bulker	60-99,999 dwt						
Bulker	35-59,999 dwt						
Bulker	10-34,999 dwt						
Bulker	-9,999 dwt						
General cargo	10,000+ dwt						
General cargo	5,000-9,999 dwt						
General cargo	-4,999 dwt						
General cargo	10,000+ dwt, 100+ TEU						
General cargo	5,000-9,999 dwt, 100+ TEU						
General cargo	-4,999 dwt, 100+ TEU						

Other dry cargo	Reefer					
Other dry cargo	Special					
Container	8,000+ TEU					
Container	5 -7,999 TEU					
Container	3 -4,999 TEU					
Container	2 -2,999 TEU					
Container	1 -1,999 TEU					
Container	-999 TEU					
Vehicle carrier	4,000+ CEU					
Vehicle carrier	-3,999 CEU					
RoRo	2,000+ lm					
RoRo	-1,999 lm					
Ferry	Pax Only, 25kn+	34,360	37,980		0.1	0.8
Ferry	Pax Only, <25kn	16,990	18,780		0.1	0.8
Ferry	RoPax, 25kn+	248,870	275,070		0.1	0.8
Ferry	RoPax, <25kn	66,540	73,550		0.1	0.8
Cruise vessel	100,000+ GT	635,360	702,240		0.1	0.8
Cruise vessel	60-99,999 GT	473,450	523,290		0.1	0.8
Cruise vessel	10-59,999 GT	190,190	210,210		0.1	0.8
Cruise vessel	2-9,999 GT	53,610	59,250		0.1	0.8
Cruise vessel	-1,999 GT	9,530	10,530		0.1	0.8

Table A2-22: Speed control of pumps and fans

		Non-recurring costs (2007 US $)		Annual recurring costs (2007 US $)		Reduction potential (%)	
		Low	High	Low	High	Low	High
Crude oil tanker	200,000+ dwt	414,860	458,530			0.2	1
Crude oil tanker	120-199,999 dwt	321,900	355,790			0.2	1
Crude oil tanker	80-119,999 dwt	275,480	304,480			0.2	1
Crude oil tanker	60-79,999 dwt	205,720	227,370			0.2	1
Crude oil tanker	10-59,999 dwt	144,770	160,010			0.2	1
Crude oil tanker	-9,999 dwt	31,100	34,370			0.2	1
Product tanker	60,000+ dwt	209,410	231,460			0.2	1
Product tanker	20-59,999 dwt	143,910	159,060			0.2	1
Product tanker	10-19,999 dwt	90,830	100,390			0.2	1
Product tanker	5-9,999 dwt	51,040	56,420			0.2	1
Product tanker	-4,999 dwt	17,330	19,150			0.2	1
Chemical tanker	20,000+ dwt	162,240	179,320			0.2	1
Chemical tanker	10-19,999 dwt	92,920	102,700			0.2	1
Chemical tanker	5 -9,999 dwt	59,100	65,320			0.2	1
Chemical tanker	-4,999 dwt	16,440	18,170			0.2	1
LPG tanker	50,000+ cbm	226,870	250,750			0.2	1
LPG tanker	-49,999 cbm	39,980	44,180			0.2	1
LNG tanker	200,000+ cbm	553,390	611,650			0.2	1
LNG tanker	-199,999 cbm	578,520	639,420			0.2	1
Other tanker		18,950	20,950			0.2	1
Bulker	200,000+ dwt	280,470	309,990			0.2	1
Bulker	100-199,999 dwt	241,660	267,100			0.2	1
Bulker	60-99,999 dwt	164,510	181,830			0.2	1
Bulker	35-59,999 dwt	133,200	147,220			0.2	1
Bulker	10-34,999 dwt	105,000	116,050			0.2	1
Bulker	-9,999 dwt	20,440	22,590			0.2	1
General cargo	10,000+ dwt	108,050	119,420			0.2	1
General cargo	5,000-9,999 dwt	59,190	65,420			0.2	1
General cargo	-4,999 dwt	10,990	12,150			0.2	1
General cargo	10,000+ dwt, 100+ TEU	110,670	122,320			0.2	1
General cargo	5,000-9,999 dwt, 100+ TEU	43,810	48,420			0.2	1
General cargo	-4,999 dwt, 100+ TEU	24,550	27,140			0.2	1

Other dry cargo	Reefer	85,080	94,030	0.2	1
Other dry cargo	Special	81,230	89,780	0.2	1
Container	8,000+ TEU	894,320	988,460	0.2	1
Container	5 -7,999 TEU	720,740	796,610	0.2	1
Container	3 -4,999 TEU	478,880	529,290	0.2	1
Container	2 -2,999 TEU	303,110	335,020	0.2	1
Container	1 -1,999 TEU	190,550	210,610	0.2	1
Container	-999 TEU	66,990	74,040	0.2	1
Vehicle carrier	4,000+ CEU	245,730	271,600	0.2	1
Vehicle carrier	-3,999 CEU	136,870	151,270	0.2	1
RoRo	2,000+ lm	191,280	211,420	0.2	1
RoRo	-1,999 lm	35,360	39,080	0.2	1
Ferry	Pax Only, 25kn+	45,820	50,640	0.2	1
Ferry	Pax Only, <25kn	22,650	25,040	0.2	1
Ferry	RoPax, 25kn+	331,830	366,760	0.2	1
Ferry	RoPax, <25kn	88,720	98,060	0.2	1
Cruise vessel	100,000+ GT	847,150	936,320	0.2	1
Cruise vessel	60-99,999 GT	631,270	697,720	0.2	1
Cruise vessel	10-59,999 GT	253,590	280,280	0.2	1
Cruise vessel	2-9,999 GT	71,480	79,000	0.2	1
Cruise vessel	-1,999 GT	12,700	14,040	0.2	1

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APPENDIX III

MARGINAL ABATEMENT COST TABLES

A3-1 Appendix III shows an example of disaggregated MAC by ship type, size, and age (hull coating 1). For other measures, to save spaces for this report, they tables are on the ICCT and SNAME websites: www.drop-in/icctmarine and http://www.sname.org/SNAME/climatechange/MACreport. For MAC and MACC, these are subject to change as we receive new data.

Table A3-1-A: The Marginal Abatement Cost of Hull Coating 1 by ship type, size, and age

				2020	MAC low reduction potential		MAC high reduction potential		2030	MAC low reduction potential		MAC high reduction	
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate
01 Crude	Tanker	B	A 200,000+ dwt	15.0	-162.4	-101.7	-208.9	-194.2	5.0	-226.3	-165.6	-272.8	-258.1
01 Crude	Tanker	B	A 200,000+ dwt	10.0	-162.4	-101.7	-208.9	-194.2	30.0	-226.3	-165.6	-272.8	-258.1
01 Crude	Tanker	B	A 200,000+ dwt	5.0	-162.4	-101.7	-208.9	-194.2	25.0	-226.3	-165.6	-272.8	-258.1
01 Crude	Tanker	B	A 200,000+ dwt	30.0	-162.4	-101.7	-208.9	-194.2	20.0	-226.3	-165.6	-272.8	-258.1
01 Crude	Tanker	B	A 200,000+ dwt	25.0	-162.4	-101.7	-208.9	-194.2	15.0	-226.3	-165.6	-272.8	-258.1
01 Crude	Tanker	B	A 200,000+ dwt	20.0	-162.4	-101.7	-208.9	-194.2	10.0	-226.3	-165.6	-272.8	-258.1
01 Crude	Tanker	B	B 120 -199,999 dwt	15.0	-172.7	-117.9	-211.4	-198.1	5.0	-236.6	-181.8	-275.3	-262.0
01 Crude	Tanker	B	B 120 -199,999 dwt	10.0	-172.7	-117.9	-211.4	-198.1	30.0	-236.6	-181.8	-275.3	-262.0
01 Crude	Tanker	B	B 120 -199,999 dwt	5.0	-172.7	-117.9	-211.4	-198.1	25.0	-236.6	-181.8	-275.3	-262.0
01 Crude	Tanker	B	B 120 -199,999 dwt	30.0	-172.7	-117.9	-211.4	-198.1	20.0	-236.6	-181.8	-275.3	-262.0
01 Crude	Tanker	B	B 120 -199,999 dwt	25.0	-172.7	-117.9	-211.4	-198.1	15.0	-236.6	-181.8	-275.3	-262.0
01 Crude	Tanker	B	B 120 -199,999 dwt	20.0	-172.7	-117.9	-211.4	-198.1	10.0	-236.6	-181.8	-275.3	-262.0
01 Crude	Tanker	B	C 80 -119,999 dwt	15.0	-176.5	-122.5	-212.3	-199.2	5.0	-240.4	-186.4	-276.2	-263.1
01 Crude	Tanker	B	C 80 -119,999 dwt	10.0	-176.5	-122.5	-212.3	-199.2	30.0	-240.4	-186.4	-276.2	-263.1
01 Crude	Tanker	B	C 80 -119,999 dwt	5.0	-176.5	-122.5	-212.3	-199.2	25.0	-240.4	-186.4	-276.2	-263.1
01 Crude	Tanker	B	C 80 -119,999 dwt	30.0	-176.5	-122.5	-212.3	-199.2	20.0	-240.4	-186.4	-276.2	-263.1
01 Crude	Tanker	B	C 80 -119,999 dwt	25.0	-176.5	-122.5	-212.3	-199.2	15.0	-240.4	-186.4	-276.2	-263.1
01 Crude	Tanker	B	C 80 -119,999 dwt	20.0	-176.5	-122.5	-212.3	-199.2	10.0	-240.4	-186.4	-276.2	-263.1
01 Crude	Tanker	B	D 60 -79,999 dwt	15.0	-174.2	-114.3	-211.7	-197.3	5.0	-238.1	-178.2	-275.6	-261.2
01 Crude	Tanker	B	D 60 -79,999 dwt	10.0	-174.2	-114.3	-211.7	-197.3	30.0	-238.1	-178.2	-275.6	-261.2
01 Crude	Tanker	B	D 60 -79,999 dwt	5.0	-174.2	-114.3	-211.7	-197.3	25.0	-238.1	-178.2	-275.6	-261.2
01 Crude	Tanker	B	D 60 -79,999 dwt	30.0	-174.2	-114.3	-211.7	-197.3	20.0	-238.1	-178.2	-275.6	-261.2
01 Crude	Tanker	B	D 60 -79,999 dwt	25.0	-174.2	-114.3	-211.7	-197.3	15.0	-238.1	-178.2	-275.6	-261.2
01 Crude	Tanker	B	D 60 -79,999 dwt	20.0	-174.2	-114.3	-211.7	-197.3	10.0	-238.1	-178.2	-275.6	-261.2
01 Crude	Tanker	B	E 10 -59,999 dwt	15.0	-172.7	-100.9	-211.3	-194.0	5.0	-236.6	-164.8	-275.2	-257.9
01 Crude	Tanker	B	E 10 -59,999 dwt	10.0	-172.7	-100.9	-211.3	-194.0	30.0	-236.6	-164.8	-275.2	-257.9
01 Crude	Tanker	B	E 10 -59,999 dwt	5.0	-172.7	-100.9	-211.3	-194.0	25.0	-236.6	-164.8	-275.2	-257.9
01 Crude	Tanker	B	E 10 -59,999 dwt	30.0	-172.7	-100.9	-211.3	-194.0	20.0	-236.6	-164.8	-275.2	-257.9
01 Crude	Tanker	B	E 10 -59,999 dwt	25.0	-172.7	-100.9	-211.3	-194.0	15.0	-236.6	-164.8	-275.2	-257.9
01 Crude	Tanker	B	E 10 -59,999 dwt	20.0	-172.7	-100.9	-211.3	-194.0	10.0	-236.6	-164.8	-275.2	-257.9
01 Crude	Tanker	S	F -9,999 dwt	15.0	-177.6	-54.2	-212.5	-182.7	5.0	-241.5	-118.1	-276.4	-246.6
01 Crude	Tanker	S	F -9,999 dwt	10.0	-177.6	-54.2	-212.5	-182.7	30.0	-241.5	-118.1	-276.4	-246.6
01 Crude	Tanker	S	F -9,999 dwt	5.0	-177.6	-54.2	-212.5	-182.7	25.0	-241.5	-118.1	-276.4	-246.6
01 Crude	Tanker	S	F -9,999 dwt	30.0	-177.6	-54.2	-212.5	-182.7	20.0	-241.5	-118.1	-276.4	-246.6
01 Crude	Tanker	S	F -9,999 dwt	25.0	-177.6	-54.2	-212.5	-182.7	15.0	-241.5	-118.1	-276.4	-246.6
01 Crude	Tanker	S	F -9,999 dwt	20.0	-177.6	-54.2	-212.5	-182.7	10.0	-241.5	-118.1	-276.4	-246.6

Table A3-1-B: The Marginal Abatement Cost of Hull Coating 1 by ship type, size, and age

				2020	MAC low reduction potential		MAC high reduction potential		2030	MAC low reduction potential		MAC high reduction	
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate
02 Products	Tanker	B	A 60,000+ dwt	15.0	-160.2	-85.8	-207.8	-189.2	5.0	-224.1	-149.7	-271.7	-253.1
02 Products	Tanker	B	A 60,000+ dwt	10.0	-160.2	-85.8	-207.8	-189.2	30.0	-224.1	-149.7	-271.7	-253.1
02 Products	Tanker	B	A 60,000+ dwt	5.0	-160.2	-85.8	-207.8	-189.2	25.0	-224.1	-149.7	-271.7	-253.1
02 Products	Tanker	B	A 60,000+ dwt	30.0	-160.2	-85.8	-207.8	-189.2	20.0	-224.1	-149.7	-271.7	-253.1
02 Products	Tanker	B	A 60,000+ dwt	25.0	-160.2	-85.8	-207.8	-189.2	15.0	-224.1	-149.7	-271.7	-253.1
02 Products	Tanker	B	A 60,000+ dwt	20.0	-160.2	-85.8	-207.8	-189.2	10.0	-224.1	-149.7	-271.7	-253.1
02 Products	Tanker	B	B 20 -59,999 dwt	15.0	-164.0	-84.7	-208.7	-188.9	5.0	-227.9	-148.6	-272.6	-252.8
02 Products	Tanker	B	B 20 -59,999 dwt	10.0	-164.0	-84.7	-208.7	-188.9	30.0	-227.9	-148.6	-272.6	-252.8
02 Products	Tanker	B	B 20 -59,999 dwt	5.0	-164.0	-84.7	-208.7	-188.9	25.0	-227.9	-148.6	-272.6	-252.8
02 Products	Tanker	B	B 20 -59,999 dwt	30.0	-164.0	-84.7	-208.7	-188.9	20.0	-227.9	-148.6	-272.6	-252.8
02 Products	Tanker	B	B 20 -59,999 dwt	25.0	-164.0	-84.7	-208.7	-188.9	15.0	-227.9	-148.6	-272.6	-252.8
02 Products	Tanker	B	B 20 -59,999 dwt	20.0	-164.0	-84.7	-208.7	-188.9	10.0	-227.9	-148.6	-272.6	-252.8
02 Products	Tanker	B	C 10 -19,999 dwt	15.0	-172.2	-90.0	-210.8	-190.2	5.0	-236.1	-153.8	-274.7	-254.1
02 Products	Tanker	B	C 10 -19,999 dwt	10.0	-172.2	-90.0	-210.8	-190.2	30.0	-236.1	-153.8	-274.7	-254.1
02 Products	Tanker	B	C 10 -19,999 dwt	5.0	-172.2	-90.0	-210.8	-190.2	25.0	-236.1	-153.8	-274.7	-254.1
02 Products	Tanker	B	C 10 -19,999 dwt	30.0	-172.2	-90.0	-210.8	-190.2	20.0	-236.1	-153.8	-274.7	-254.1
02 Products	Tanker	B	C 10 -19,999 dwt	25.0	-172.2	-90.0	-210.8	-190.2	15.0	-236.1	-153.8	-274.7	-254.1
02 Products	Tanker	B	C 10 -19,999 dwt	20.0	-172.2	-90.0	-210.8	-190.2	10.0	-236.1	-153.8	-274.7	-254.1
02 Products	Tanker	S	D 5 -9,999 dwt	15.0	-170.8	-65.1	-210.4	-184.0	5.0	-234.7	-129.0	-274.3	-247.9
02 Products	Tanker	S	D 5 -9,999 dwt	10.0	-170.8	-65.1	-210.4	-184.0	30.0	-234.7	-129.0	-274.3	-247.9
02 Products	Tanker	S	D 5 -9,999 dwt	5.0	-170.8	-65.1	-210.4	-184.0	25.0	-234.7	-129.0	-274.3	-247.9
02 Products	Tanker	S	D 5 -9,999 dwt	30.0	-170.8	-65.1	-210.4	-184.0	20.0	-234.7	-129.0	-274.3	-247.9
02 Products	Tanker	S	D 5 -9,999 dwt	25.0	-170.8	-65.1	-210.4	-184.0	15.0	-234.7	-129.0	-274.3	-247.9
02 Products	Tanker	S	D 5 -9,999 dwt	20.0	-170.8	-65.1	-210.4	-184.0	10.0	-234.7	-129.0	-274.3	-247.9
02 Products	Tanker	S	E -4,999 dwt	15.0	-162.4	42.7	-208.3	-157.0	5.0	-226.3	-21.2	-272.2	-220.9
02 Products	Tanker	S	E -4,999 dwt	10.0	-162.4	42.7	-208.3	-157.0	30.0	-226.3	-21.2	-272.2	-220.9
02 Products	Tanker	S	E -4,999 dwt	5.0	-162.4	42.7	-208.3	-157.0	25.0	-226.3	-21.2	-272.2	-220.9
02 Products	Tanker	S	E -4,999 dwt	30.0	-162.4	42.7	-208.3	-157.0	20.0	-226.3	-21.2	-272.2	-220.9
02 Products	Tanker	S	E -4,999 dwt	25.0	-162.4	42.7	-208.3	-157.0	15.0	-226.3	-21.2	-272.2	-220.9
02 Products	Tanker	S	E -4,999 dwt	20.0	-162.4	42.7	-208.3	-157.0	10.0	-226.3	-21.2	-272.2	-220.9

Table A3-1-C: The Marginal Abatement Cost of Hull Coating 1 by ship type, size, and age

				2020	MAC low reduction potential		MAC high reduction potential		2030	MAC low reduction potential		MAC high reduction	
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate
03 Chemical	Tanker	B	A 20,000+ dwt	15.0	-169.8	-79.0	-210.2	-187.5	5.0	-233.7	-142.9	-274.1	-251.4
03 Chemical	Tanker	B	A 20,000+ dwt	10.0	-169.8	-79.0	-210.2	-187.5	30.0	-233.7	-142.9	-274.1	-251.4
03 Chemical	Tanker	B	A 20,000+ dwt	5.0	-169.8	-79.0	-210.2	-187.5	25.0	-233.7	-142.9	-274.1	-251.4
03 Chemical	Tanker	B	A 20,000+ dwt	30.0	-169.8	-79.0	-210.2	-187.5	20.0	-233.7	-142.9	-274.1	-251.4
03 Chemical	Tanker	B	A 20,000+ dwt	25.0	-169.8	-79.0	-210.2	-187.5	15.0	-233.7	-142.9	-274.1	-251.4
03 Chemical	Tanker	B	A 20,000+ dwt	20.0	-169.8	-79.0	-210.2	-187.5	10.0	-233.7	-142.9	-274.1	-251.4
03 Chemical	Tanker	B	B 10-19,999 dwt	15.0	-174.7	-65.7	-211.4	-184.2	5.0	-238.6	-129.6	-275.3	-248.1
03 Chemical	Tanker	B	B 10-19,999 dwt	10.0	-174.7	-65.7	-211.4	-184.2	30.0	-238.6	-129.6	-275.3	-248.1
03 Chemical	Tanker	B	B 10-19,999 dwt	5.0	-174.7	-65.7	-211.4	-184.2	25.0	-238.6	-129.6	-275.3	-248.1
03 Chemical	Tanker	B	B 10-19,999 dwt	30.0	-174.7	-65.7	-211.4	-184.2	20.0	-238.6	-129.6	-275.3	-248.1
03 Chemical	Tanker	B	B 10-19,999 dwt	25.0	-174.7	-65.7	-211.4	-184.2	15.0	-238.6	-129.6	-275.3	-248.1
03 Chemical	Tanker	B	B 10-19,999 dwt	20.0	-174.7	-65.7	-211.4	-184.2	10.0	-238.6	-129.6	-275.3	-248.1
03 Chemical	Tanker	S	C 5-9,999 dwt	15.0	-175.7	-40.7	-211.7	-177.9	5.0	-239.6	-104.6	-275.6	-241.8
03 Chemical	Tanker	S	C 5-9,999 dwt	10.0	-175.7	-40.7	-211.7	-177.9	30.0	-239.6	-104.6	-275.6	-241.8
03 Chemical	Tanker	S	C 5-9,999 dwt	5.0	-175.7	-40.7	-211.7	-177.9	25.0	-239.6	-104.6	-275.6	-241.8
03 Chemical	Tanker	S	C 5-9,999 dwt	30.0	-175.7	-40.7	-211.7	-177.9	20.0	-239.6	-104.6	-275.6	-241.8
03 Chemical	Tanker	S	C 5-9,999 dwt	25.0	-175.7	-40.7	-211.7	-177.9	15.0	-239.6	-104.6	-275.6	-241.8
03 Chemical	Tanker	S	C 5-9,999 dwt	20.0	-175.7	-40.7	-211.7	-177.9	10.0	-239.6	-104.6	-275.6	-241.8
03 Chemical	Tanker	S	D -4,999 dwt	15.0	-148.2	198.1	-204.8	-118.2	5.0	-212.1	134.2	-268.7	-182.1
03 Chemical	Tanker	S	D -4,999 dwt	10.0	-148.2	198.1	-204.8	-118.2	30.0	-212.1	134.2	-268.7	-182.1
03 Chemical	Tanker	S	D -4,999 dwt	5.0	-148.2	198.1	-204.8	-118.2	25.0	-212.1	134.2	-268.7	-182.1
03 Chemical	Tanker	S	D -4,999 dwt	30.0	-148.2	198.1	-204.8	-118.2	20.0	-212.1	134.2	-268.7	-182.1
03 Chemical	Tanker	S	D -4,999 dwt	25.0	-148.2	198.1	-204.8	-118.2	15.0	-212.1	134.2	-268.7	-182.1
03 Chemical	Tanker	S	D -4,999 dwt	20.0	-148.2	198.1	-204.8	-118.2	10.0	-212.1	134.2	-268.7	-182.1
04 LPG	Tanker	B	A 50,000+ cbm	15.0	-139.6	-15.5	-203.9	-174.7	5.0	-203.4	-79.4	-267.8	-238.6
04 LPG	Tanker	B	A 50,000+ cbm	10.0	-139.6	-15.5	-203.9	-174.7	30.0	-203.4	-79.4	-267.8	-238.6
04 LPG	Tanker	B	A 50,000+ cbm	5.0	-139.6	-15.5	-203.9	-174.7	25.0	-203.4	-79.4	-267.8	-238.6
04 LPG	Tanker	B	A 50,000+ cbm	30.0	-139.6	-15.5	-203.9	-174.7	20.0	-203.4	-79.4	-267.8	-238.6
04 LPG	Tanker	B	A 50,000+ cbm	25.0	-139.6	-15.5	-203.9	-174.7	15.0	-203.4	-79.4	-267.8	-238.6
04 LPG	Tanker	B	A 50,000+ cbm	20.0	-139.6	-15.5	-203.9	-174.7	10.0	-203.4	-79.4	-267.8	-238.6
04 LPG	Tanker	S	B -49,999 cbm	15.0	-113.7	321.8	-197.8	-95.3	5.0	-177.6	257.9	-261.7	-159.2
04 LPG	Tanker	S	B -49,999 cbm	10.0	-113.7	321.8	-197.8	-95.3	30.0	-177.6	257.9	-261.7	-159.2
04 LPG	Tanker	S	B -49,999 cbm	5.0	-113.7	321.8	-197.8	-95.3	25.0	-177.6	257.9	-261.7	-159.2
04 LPG	Tanker	S	B -49,999 cbm	30.0	-113.7	321.8	-197.8	-95.3	20.0	-177.6	257.9	-261.7	-159.2
04 LPG	Tanker	S	B -49,999 cbm	25.0	-113.7	321.8	-197.8	-95.3	15.0	-177.6	257.9	-261.7	-159.2
04 LPG	Tanker	S	B -49,999 cbm	20.0	-113.7	321.8	-197.8	-95.3	10.0	-177.6	257.9	-261.7	-159.2

Table A3-1-D: The Marginal Abatement Cost of Hull Coating 1 by ship type, size, and age

				2020	MAC low reduction potential		MAC high reduction potential		2030	MAC low reduction potential		MAC high reduction	
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate
05 LNG	Tanker	B	A 200,000+ cbm	15.0	-150.3	13.1	-206.4	-167.9	5.0	-214.2	-50.8	-270.3	-231.8
05 LNG	Tanker	B	A 200,000+ cbm	10.0	-150.3	13.1	-206.4	-167.9	30.0	-214.2	-50.8	-270.3	-231.8
05 LNG	Tanker	B	A 200,000+ cbm	5.0	-150.3	13.1	-206.4	-167.9	25.0	-214.2	-50.8	-270.3	-231.8
05 LNG	Tanker	B	A 200,000+ cbm	30.0	-150.3	13.1	-206.4	-167.9	20.0	-214.2	-50.8	-270.3	-231.8
05 LNG	Tanker	B	A 200,000+ cbm	25.0	-150.3	13.1	-206.4	-167.9	15.0	-214.2	-50.8	-270.3	-231.8
05 LNG	Tanker	B	A 200,000+ cbm	20.0	-150.3	13.1	-206.4	-167.9	10.0	-214.2	-50.8	-270.3	-231.8
05 LNG	Tanker	B	B -199,999 cbm	15.0	-169.9	-52.7	-211.0	-183.4	5.0	-233.7	-116.6	-274.9	-247.3
05 LNG	Tanker	B	B -199,999 cbm	10.0	-169.9	-52.7	-211.0	-183.4	30.0	-233.7	-116.6	-274.9	-247.3
05 LNG	Tanker	B	B -199,999 cbm	5.0	-169.9	-52.7	-211.0	-183.4	25.0	-233.7	-116.6	-274.9	-247.3
05 LNG	Tanker	B	B -199,999 cbm	30.0	-169.9	-52.7	-211.0	-183.4	20.0	-233.7	-116.6	-274.9	-247.3
05 LNG	Tanker	B	B -199,999 cbm	25.0	-169.9	-52.7	-211.0	-183.4	15.0	-233.7	-116.6	-274.9	-247.3
05 LNG	Tanker	B	B -199,999 cbm	20.0	-169.9	-52.7	-211.0	-183.4	10.0	-233.7	-116.6	-274.9	-247.3
06 Other tanker	Tanker	S	B Other	15.0	-93.6	478.9	-191.1	-48.0	5.0	-157.5	415.0	-255.0	-111.9
06 Other tanker	Tanker	S	B Other	10.0	-93.6	478.9	-191.1	-48.0	30.0	-157.5	415.0	-255.0	-111.9
06 Other tanker	Tanker	S	B Other	5.0	-93.6	478.9	-191.1	-48.0	25.0	-157.5	415.0	-255.0	-111.9
06 Other tanker	Tanker	S	B Other	30.0	-93.6	478.9	-191.1	-48.0	20.0	-157.5	415.0	-255.0	-111.9
06 Other tanker	Tanker	S	B Other	25.0	-93.6	478.9	-191.1	-48.0	15.0	-157.5	415.0	-255.0	-111.9
06 Other tanker	Tanker	S	B Other	20.0	-93.6	478.9	-191.1	-48.0	10.0	-157.5	415.0	-255.0	-111.9

Table A3-1-E: The Marginal Abatement Cost of Hull Coating 1 by ship type, size, and age

				2020	MAC low reduction potential		MAC high reduction potential		2030	MAC low reduction potential		MAC high reduction	
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate
07 Bulker	Bulker	B	A 200,000+ dwt	15.0	-120.3	-38.2	-197.8	-177.3	5.0	-184.2	-102.1	-261.7	-241.2
07 Bulker	Bulker	B	A 200,000+ dwt	10.0	-120.3	-38.2	-197.8	-177.3	30.0	-184.2	-102.1	-261.7	-241.2
07 Bulker	Bulker	B	A 200,000+ dwt	5.0	-120.3	-38.2	-197.8	-177.3	25.0	-184.2	-102.1	-261.7	-241.2
07 Bulker	Bulker	B	A 200,000+ dwt	30.0	-120.3	-38.2	-197.8	-177.3	20.0	-184.2	-102.1	-261.7	-241.2
07 Bulker	Bulker	B	A 200,000+ dwt	25.0	-120.3	-38.2	-197.8	-177.3	15.0	-184.2	-102.1	-261.7	-241.2
07 Bulker	Bulker	B	A 200,000+ dwt	20.0	-120.3	-38.2	-197.8	-177.3	10.0	-184.2	-102.1	-261.7	-241.2
07 Bulker	Bulker	B	B 100 -199,999 dwt	15.0	-126.4	-37.3	-199.3	-177.0	5.0	-190.3	-101.2	-263.2	-240.9
07 Bulker	Bulker	B	B 100 -199,999 dwt	10.0	-126.4	-37.3	-199.3	-177.0	30.0	-190.3	-101.2	-263.2	-240.9
07 Bulker	Bulker	B	B 100 -199,999 dwt	5.0	-126.4	-37.3	-199.3	-177.0	25.0	-190.3	-101.2	-263.2	-240.9
07 Bulker	Bulker	B	B 100 -199,999 dwt	30.0	-126.4	-37.3	-199.3	-177.0	20.0	-190.3	-101.2	-263.2	-240.9
07 Bulker	Bulker	B	B 100 -199,999 dwt	25.0	-126.4	-37.3	-199.3	-177.0	15.0	-190.3	-101.2	-263.2	-240.9
07 Bulker	Bulker	B	B 100 -199,999 dwt	20.0	-126.4	-37.3	-199.3	-177.0	10.0	-190.3	-101.2	-263.2	-240.9
07 Bulker	Bulker	B	C 60 -99,999 dwt	15.0	-136.9	-50.9	-202.0	-180.5	5.0	-200.8	-114.8	-265.9	-244.4
07 Bulker	Bulker	B	C 60 -99,999 dwt	10.0	-136.9	-50.9	-202.0	-180.5	30.0	-200.8	-114.8	-265.9	-244.4
07 Bulker	Bulker	B	C 60 -99,999 dwt	5.0	-136.9	-50.9	-202.0	-180.5	25.0	-200.8	-114.8	-265.9	-244.4
07 Bulker	Bulker	B	C 60 -99,999 dwt	30.0	-136.9	-50.9	-202.0	-180.5	20.0	-200.8	-114.8	-265.9	-244.4
07 Bulker	Bulker	B	C 60 -99,999 dwt	25.0	-136.9	-50.9	-202.0	-180.5	15.0	-200.8	-114.8	-265.9	-244.4
07 Bulker	Bulker	B	C 60 -99,999 dwt	20.0	-136.9	-50.9	-202.0	-180.5	10.0	-200.8	-114.8	-265.9	-244.4
07 Bulker	Bulker	B	D 35 -59,999 dwt	15.0	-139.4	-47.7	-202.6	-179.7	5.0	-203.3	-111.6	-266.5	-243.6
07 Bulker	Bulker	B	D 35 -59,999 dwt	10.0	-139.4	-47.7	-202.6	-179.7	30.0	-203.3	-111.6	-266.5	-243.6
07 Bulker	Bulker	B	D 35 -59,999 dwt	5.0	-139.4	-47.7	-202.6	-179.7	25.0	-203.3	-111.6	-266.5	-243.6
07 Bulker	Bulker	B	D 35 -59,999 dwt	30.0	-139.4	-47.7	-202.6	-179.7	20.0	-203.3	-111.6	-266.5	-243.6
07 Bulker	Bulker	B	D 35 -59,999 dwt	25.0	-139.4	-47.7	-202.6	-179.7	15.0	-203.3	-111.6	-266.5	-243.6
07 Bulker	Bulker	B	D 35 -59,999 dwt	20.0	-139.4	-47.7	-202.6	-179.7	10.0	-203.3	-111.6	-266.5	-243.6
07 Bulker	Bulker	B	E 10 -34,999 dwt	15.0	-151.4	-56.6	-205.6	-181.9	5.0	-215.3	-120.5	-269.5	-245.8
07 Bulker	Bulker	B	E 10 -34,999 dwt	10.0	-151.4	-56.6	-205.6	-181.9	30.0	-215.3	-120.5	-269.5	-245.8
07 Bulker	Bulker	B	E 10 -34,999 dwt	5.0	-151.4	-56.6	-205.6	-181.9	25.0	-215.3	-120.5	-269.5	-245.8
07 Bulker	Bulker	B	E 10 -34,999 dwt	30.0	-151.4	-56.6	-205.6	-181.9	20.0	-215.3	-120.5	-269.5	-245.8
07 Bulker	Bulker	B	E 10 -34,999 dwt	25.0	-151.4	-56.6	-205.6	-181.9	15.0	-215.3	-120.5	-269.5	-245.8
07 Bulker	Bulker	B	E 10 -34,999 dwt	20.0	-151.4	-56.6	-205.6	-181.9	10.0	-215.3	-120.5	-269.5	-245.8
07 Bulker	Bulker	S	F -9,999 dwt	15.0	-130.1	135.0	-200.3	-134.0	5.0	-194.0	71.1	-264.2	-197.9
07 Bulker	Bulker	S	F -9,999 dwt	10.0	-130.1	135.0	-200.3	-134.0	30.0	-194.0	71.1	-264.2	-197.9
07 Bulker	Bulker	S	F -9,999 dwt	5.0	-130.1	135.0	-200.3	-134.0	25.0	-194.0	71.1	-264.2	-197.9
07 Bulker	Bulker	S	F -9,999 dwt	30.0	-130.1	135.0	-200.3	-134.0	20.0	-194.0	71.1	-264.2	-197.9
07 Bulker	Bulker	S	F -9,999 dwt	25.0	-130.1	135.0	-200.3	-134.0	15.0	-194.0	71.1	-264.2	-197.9
07 Bulker	Bulker	S	F -9,999 dwt	20.0	-130.1	135.0	-200.3	-134.0	10.0	-194.0	71.1	-264.2	-197.9

Table A3-1-F: The Marginal Abatement Cost of Hull Coating 1 by ship type, size, and age

				2020	MAC low reduction potential		MAC high reduction potential		2030	MAC low reduction potential		MAC high reduction	
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate
08 General cargo	General Cargo	B	A 10,000+ dwt	15.0	-166.1	-78.5	-209.2	-187.3	5.0	-230.0	-142.4	-273.1	-251.2
08 General cargo	General Cargo	B	A 10,000+ dwt	10.0	-166.1	-78.5	-209.2	-187.3	30.0	-230.0	-142.4	-273.1	-251.2
08 General cargo	General Cargo	B	A 10,000+ dwt	5.0	-166.1	-78.5	-209.2	-187.3	25.0	-230.0	-142.4	-273.1	-251.2
08 General cargo	General Cargo	B	A 10,000+ dwt	30.0	-166.1	-78.5	-209.2	-187.3	20.0	-230.0	-142.4	-273.1	-251.2
08 General cargo	General Cargo	B	A 10,000+ dwt	25.0	-166.1	-78.5	-209.2	-187.3	15.0	-230.0	-142.4	-273.1	-251.2
08 General cargo	General Cargo	B	A 10,000+ dwt	20.0	-166.1	-78.5	-209.2	-187.3	10.0	-230.0	-142.4	-273.1	-251.2
08 General cargo	General Cargo	S	B 5,000-9,999 dwt	15.0	-165.4	-61.2	-209.1	-183.0	5.0	-229.2	-125.1	-273.0	-246.9
08 General cargo	General Cargo	S	B 5,000-9,999 dwt	10.0	-165.4	-61.2	-209.1	-183.0	30.0	-229.2	-125.1	-273.0	-246.9
08 General cargo	General Cargo	S	B 5,000-9,999 dwt	5.0	-165.4	-61.2	-209.1	-183.0	25.0	-229.2	-125.1	-273.0	-246.9
08 General cargo	General Cargo	S	B 5,000-9,999 dwt	30.0	-165.4	-61.2	-209.1	-183.0	20.0	-229.2	-125.1	-273.0	-246.9
08 General cargo	General Cargo	S	B 5,000-9,999 dwt	25.0	-165.4	-61.2	-209.1	-183.0	15.0	-229.2	-125.1	-273.0	-246.9
08 General cargo	General Cargo	S	B 5,000-9,999 dwt	20.0	-165.4	-61.2	-209.1	-183.0	10.0	-229.2	-125.1	-273.0	-246.9
08 General cargo	General Cargo	S	C -4,999 dwt	15.0	-107.5	251.5	-194.6	-104.9	5.0	-171.4	187.6	-258.5	-168.8
08 General cargo	General Cargo	S	C -4,999 dwt	10.0	-107.5	251.5	-194.6	-104.9	30.0	-171.4	187.6	-258.5	-168.8
08 General cargo	General Cargo	S	C -4,999 dwt	5.0	-107.5	251.5	-194.6	-104.9	25.0	-171.4	187.6	-258.5	-168.8
08 General cargo	General Cargo	S	C -4,999 dwt	30.0	-107.5	251.5	-194.6	-104.9	20.0	-171.4	187.6	-258.5	-168.8
08 General cargo	General Cargo	S	C -4,999 dwt	25.0	-107.5	251.5	-194.6	-104.9	15.0	-171.4	187.6	-258.5	-168.8
08 General cargo	General Cargo	S	C -4,999 dwt	20.0	-107.5	251.5	-194.6	-104.9	10.0	-171.4	187.6	-258.5	-168.8
08 General cargo	General Cargo	B	D 10,000+ dwt, 100+ TEU	15.0	-154.2	-70.6	-206.3	-185.4	5.0	-218.1	-134.5	-270.2	-249.3
08 General cargo	General Cargo	B	D 10,000+ dwt, 100+ TEU	10.0	-154.2	-70.6	-206.3	-185.4	30.0	-218.1	-134.5	-270.2	-249.3
08 General cargo	General Cargo	B	D 10,000+ dwt, 100+ TEU	5.0	-154.2	-70.6	-206.3	-185.4	25.0	-218.1	-134.5	-270.2	-249.3
08 General cargo	General Cargo	B	D 10,000+ dwt, 100+ TEU	30.0	-154.2	-70.6	-206.3	-185.4	20.0	-218.1	-134.5	-270.2	-249.3
08 General cargo	General Cargo	B	D 10,000+ dwt, 100+ TEU	25.0	-154.2	-70.6	-206.3	-185.4	15.0	-218.1	-134.5	-270.2	-249.3
08 General cargo	General Cargo	B	D 10,000+ dwt, 100+ TEU	20.0	-154.2	-70.6	-206.3	-185.4	10.0	-218.1	-134.5	-270.2	-249.3
08 General cargo	General Cargo	S	E 5,000-9,999 dwt, 100+ TEU	15.0	-138.4	-6.1	-202.3	-169.3	5.0	-202.3	-70.0	-266.2	-233.2
08 General cargo	General Cargo	S	E 5,000-9,999 dwt, 100+ TEU	10.0	-138.4	-6.1	-202.3	-169.3	30.0	-202.3	-70.0	-266.2	-233.2
08 General cargo	General Cargo	S	E 5,000-9,999 dwt, 100+ TEU	5.0	-138.4	-6.1	-202.3	-169.3	25.0	-202.3	-70.0	-266.2	-233.2
08 General cargo	General Cargo	S	E 5,000-9,999 dwt, 100+ TEU	30.0	-138.4	-6.1	-202.3	-169.3	20.0	-202.3	-70.0	-266.2	-233.2
08 General cargo	General Cargo	S	E 5,000-9,999 dwt, 100+ TEU	25.0	-138.4	-6.1	-202.3	-169.3	15.0	-202.3	-70.0	-266.2	-233.2
08 General cargo	General Cargo	S	E 5,000-9,999 dwt, 100+ TEU	20.0	-138.4	-6.1	-202.3	-169.3	10.0	-202.3	-70.0	-266.2	-233.2
08 General cargo	General Cargo	S	F -4,999 dwt, 100+ TEU	15.0	-126.1	59.8	-199.2	-152.8	5.0	-190.0	-4.1	-263.1	-216.7
08 General cargo	General Cargo	S	F -4,999 dwt, 100+ TEU	10.0	-126.1	59.8	-199.2	-152.8	30.0	-190.0	-4.1	-263.1	-216.7
08 General cargo	General Cargo	S	F -4,999 dwt, 100+ TEU	5.0	-126.1	59.8	-199.2	-152.8	25.0	-190.0	-4.1	-263.1	-216.7
08 General cargo	General Cargo	S	F -4,999 dwt, 100+ TEU	30.0	-126.1	59.8	-199.2	-152.8	20.0	-190.0	-4.1	-263.1	-216.7
08 General cargo	General Cargo	S	F -4,999 dwt, 100+ TEU	25.0	-126.1	59.8	-199.2	-152.8	15.0	-190.0	-4.1	-263.1	-216.7
08 General cargo	General Cargo	S	F -4,999 dwt, 100+ TEU	20.0	-126.1	59.8	-199.2	-152.8	10.0	-190.0	-4.1	-263.1	-216.7

Table A3-1-G: The Marginal Abatement Cost of Hull Coating 1 by ship type, size, and age

				2020	MAC low reduction potential		MAC high reduction potential		2030	MAC low reduction potential		MAC high reduction	
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate
09 Other dry	General Cargo	S	A Reefer	15.0	-170.9	-37.5	-210.4	-177.1	5.0	-234.8	-101.4	-274.3	-241.0
09 Other dry	General Cargo	S	A Reefer	10.0	-170.9	-37.5	-210.4	-177.1	30.0	-234.8	-101.4	-274.3	-241.0
09 Other dry	General Cargo	S	A Reefer	5.0	-170.9	-37.5	-210.4	-177.1	25.0	-234.8	-101.4	-274.3	-241.0
09 Other dry	General Cargo	S	A Reefer	30.0	-170.9	-37.5	-210.4	-177.1	20.0	-234.8	-101.4	-274.3	-241.0
09 Other dry	General Cargo	S	A Reefer	25.0	-170.9	-37.5	-210.4	-177.1	15.0	-234.8	-101.4	-274.3	-241.0
09 Other dry	General Cargo	S	A Reefer	20.0	-170.9	-37.5	-210.4	-177.1	10.0	-234.8	-101.4	-274.3	-241.0
09 Other dry	General Cargo	S	C Special	15.0	-123.4	26.2	-198.6	-161.2	5.0	-187.3	-37.7	-262.5	-225.1
09 Other dry	General Cargo	S	C Special	10.0	-123.4	26.2	-198.6	-161.2	30.0	-187.3	-37.7	-262.5	-225.1
09 Other dry	General Cargo	S	C Special	5.0	-123.4	26.2	-198.6	-161.2	25.0	-187.3	-37.7	-262.5	-225.1
09 Other dry	General Cargo	S	C Special	30.0	-123.4	26.2	-198.6	-161.2	20.0	-187.3	-37.7	-262.5	-225.1
09 Other dry	General Cargo	S	C Special	25.0	-123.4	26.2	-198.6	-161.2	15.0	-187.3	-37.7	-262.5	-225.1
09 Other dry	General Cargo	S	C Special	20.0	-123.4	26.2	-198.6	-161.2	10.0	-187.3	-37.7	-262.5	-225.1

Table A3-1-H: The Marginal Abatement Cost of Hull Coating 1 by ship type, size, and age

				2020	MAC low reduction potential		MAC high reduction potential		2030	MAC low reduction potential		MAC high reduction	
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate
10 Container	Unitized	C	A 8,000+ teu	15.0	-198.9	-170.2	-216.9	-209.1	5.0	-262.8	-234.1	-280.8	-273.0
10 Container	Unitized	C	A 8,000+ teu	10.0	-198.9	-170.2	-216.9	-209.1	30.0	-262.8	-234.1	-280.8	-273.0
10 Container	Unitized	C	A 8,000+ teu	5.0	-198.9	-170.2	-216.9	-209.1	25.0	-262.8	-234.1	-280.8	-273.0
10 Container	Unitized	C	A 8,000+ teu	30.0	-198.9	-170.2	-216.9	-209.1	20.0	-262.8	-234.1	-280.8	-273.0
10 Container	Unitized	C	A 8,000+ teu	25.0	-198.9	-170.2	-216.9	-209.1	15.0	-262.8	-234.1	-280.8	-273.0
10 Container	Unitized	C	A 8,000+ teu	20.0	-198.9	-170.2	-216.9	-209.1	10.0	-262.8	-234.1	-280.8	-273.0
10 Container	Unitized	C	B 5 -7,999 teu	15.0	-199.4	-171.3	-217.0	-209.4	5.0	-263.3	-235.2	-280.9	-273.3
10 Container	Unitized	C	B 5 -7,999 teu	10.0	-199.4	-171.3	-217.0	-209.4	30.0	-263.3	-235.2	-280.9	-273.3
10 Container	Unitized	C	B 5 -7,999 teu	5.0	-199.4	-171.3	-217.0	-209.4	25.0	-263.3	-235.2	-280.9	-273.3
10 Container	Unitized	C	B 5 -7,999 teu	30.0	-199.4	-171.3	-217.0	-209.4	20.0	-263.3	-235.2	-280.9	-273.3
10 Container	Unitized	C	B 5 -7,999 teu	25.0	-199.4	-171.3	-217.0	-209.4	15.0	-263.3	-235.2	-280.9	-273.3
10 Container	Unitized	C	B 5 -7,999 teu	20.0	-199.4	-171.3	-217.0	-209.4	10.0	-263.3	-235.2	-280.9	-273.3
10 Container	Unitized	C	C 3 -4,999 teu	15.0	-196.5	-172.8	-216.2	-209.8	5.0	-260.4	-236.7	-280.1	-273.7
10 Container	Unitized	C	C 3 -4,999 teu	10.0	-196.5	-172.8	-216.2	-209.8	30.0	-260.4	-236.7	-280.1	-273.7
10 Container	Unitized	C	C 3 -4,999 teu	5.0	-196.5	-172.8	-216.2	-209.8	25.0	-260.4	-236.7	-280.1	-273.7
10 Container	Unitized	C	C 3 -4,999 teu	30.0	-196.5	-172.8	-216.2	-209.8	20.0	-260.4	-236.7	-280.1	-273.7
10 Container	Unitized	C	C 3 -4,999 teu	25.0	-196.5	-172.8	-216.2	-209.8	15.0	-260.4	-236.7	-280.1	-273.7
10 Container	Unitized	C	C 3 -4,999 teu	20.0	-196.5	-172.8	-216.2	-209.8	10.0	-260.4	-236.7	-280.1	-273.7
10 Container	Unitized	C	D 2 -2,999 teu	15.0	-191.5	-154.3	-214.9	-204.7	5.0	-255.4	-218.2	-278.8	-268.6
10 Container	Unitized	C	D 2 -2,999 teu	10.0	-191.5	-154.3	-214.9	-204.7	30.0	-255.4	-218.2	-278.8	-268.6
10 Container	Unitized	C	D 2 -2,999 teu	5.0	-191.5	-154.3	-214.9	-204.7	25.0	-255.4	-218.2	-278.8	-268.6
10 Container	Unitized	C	D 2 -2,999 teu	30.0	-191.5	-154.3	-214.9	-204.7	20.0	-255.4	-218.2	-278.8	-268.6
10 Container	Unitized	C	D 2 -2,999 teu	25.0	-191.5	-154.3	-214.9	-204.7	15.0	-255.4	-218.2	-278.8	-268.6
10 Container	Unitized	C	D 2 -2,999 teu	20.0	-191.5	-154.3	-214.9	-204.7	10.0	-255.4	-218.2	-278.8	-268.6
10 Container	Unitized	C	E 1 -1,999 teu	15.0	-188.9	-144.8	-214.2	-202.1	5.0	-252.8	-208.7	-278.1	-266.0
10 Container	Unitized	C	E 1 -1,999 teu	10.0	-188.9	-144.8	-214.2	-202.1	30.0	-252.8	-208.7	-278.1	-266.0
10 Container	Unitized	C	E 1 -1,999 teu	5.0	-188.9	-144.8	-214.2	-202.1	25.0	-252.8	-208.7	-278.1	-266.0
10 Container	Unitized	C	E 1 -1,999 teu	30.0	-188.9	-144.8	-214.2	-202.1	20.0	-252.8	-208.7	-278.1	-266.0
10 Container	Unitized	C	E 1 -1,999 teu	25.0	-188.9	-144.8	-214.2	-202.1	15.0	-252.8	-208.7	-278.1	-266.0
10 Container	Unitized	C	E 1 -1,999 teu	20.0	-188.9	-144.8	-214.2	-202.1	10.0	-252.8	-208.7	-278.1	-266.0
10 Container	Unitized	C	F -999 teu	15.0	-167.9	-92.3	-208.4	-187.8	5.0	-231.8	-156.2	-272.3	-251.7
10 Container	Unitized	C	F -999 teu	10.0	-167.9	-92.3	-208.4	-187.8	30.0	-231.8	-156.2	-272.3	-251.7
10 Container	Unitized	C	F -999 teu	5.0	-167.9	-92.3	-208.4	-187.8	25.0	-231.8	-156.2	-272.3	-251.7
10 Container	Unitized	C	F -999 teu	30.0	-167.9	-92.3	-208.4	-187.8	20.0	-231.8	-156.2	-272.3	-251.7
10 Container	Unitized	C	F -999 teu	25.0	-167.9	-92.3	-208.4	-187.8	15.0	-231.8	-156.2	-272.3	-251.7
10 Container	Unitized	C	F -999 teu	20.0	-167.9	-92.3	-208.4	-187.8	10.0	-231.8	-156.2	-272.3	-251.7

Table A3-1-I: The Marginal Abatement Cost of Hull Coating 1 by ship type, size, and age

				2020	MAC low reduction potential		MAC high reduction potential		2030	MAC low reduction potential		MAC high reduction	
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate
11 Vehicle	Unitized	B	A 4,000+ ceu	15.0	-137.1	-36.3	-202.0	-176.8	5.0	-201.0	-100.2	-265.9	-240.7
11 Vehicle	Unitized	B	A 4,000+ ceu	10.0	-137.1	-36.3	-202.0	-176.8	30.0	-201.0	-100.2	-265.9	-240.7
11 Vehicle	Unitized	B	A 4,000+ ceu	5.0	-137.1	-36.3	-202.0	-176.8	25.0	-201.0	-100.2	-265.9	-240.7
11 Vehicle	Unitized	B	A 4,000+ ceu	30.0	-137.1	-36.3	-202.0	-176.8	20.0	-201.0	-100.2	-265.9	-240.7
11 Vehicle	Unitized	B	A 4,000+ ceu	25.0	-137.1	-36.3	-202.0	-176.8	15.0	-201.0	-100.2	-265.9	-240.7
11 Vehicle	Unitized	B	A 4,000+ ceu	20.0	-137.1	-36.3	-202.0	-176.8	10.0	-201.0	-100.2	-265.9	-240.7
11 Vehicle	Unitized	B	B -3,999 ceu	15.0	-139.4	-30.4	-202.6	-175.3	5.0	-203.3	-94.3	-266.5	-239.2
11 Vehicle	Unitized	B	B -3,999 ceu	10.0	-139.4	-30.4	-202.6	-175.3	30.0	-203.3	-94.3	-266.5	-239.2
11 Vehicle	Unitized	B	B -3,999 ceu	5.0	-139.4	-30.4	-202.6	-175.3	25.0	-203.3	-94.3	-266.5	-239.2
11 Vehicle	Unitized	B	B -3,999 ceu	30.0	-139.4	-30.4	-202.6	-175.3	20.0	-203.3	-94.3	-266.5	-239.2
11 Vehicle	Unitized	B	B -3,999 ceu	25.0	-139.4	-30.4	-202.6	-175.3	15.0	-203.3	-94.3	-266.5	-239.2
11 Vehicle	Unitized	B	B -3,999 ceu	20.0	-139.4	-30.4	-202.6	-175.3	10.0	-203.3	-94.3	-266.5	-239.2
12 Roro	Unitized	B	A 2,000+ lm	15.0	-153.7	-65.4	-206.2	-184.1	5.0	-217.6	-129.3	-270.1	-248.0
13 Roro	Unitized	B	A 2,000+ lm	10.0	-153.7	-65.4	-206.2	-184.1	30.0	-217.6	-129.3	-270.1	-248.0
14 Roro	Unitized	B	A 2,000+ lm	5.0	-153.7	-65.4	-206.2	-184.1	25.0	-217.6	-129.3	-270.1	-248.0
15 Roro	Unitized	B	A 2,000+ lm	30.0	-153.7	-65.4	-206.2	-184.1	20.0	-217.6	-129.3	-270.1	-248.0
16 Roro	Unitized	B	A 2,000+ lm	25.0	-153.7	-65.4	-206.2	-184.1	15.0	-217.6	-129.3	-270.1	-248.0
17 Roro	Unitized	B	A 2,000+ lm	20.0	-153.7	-65.4	-206.2	-184.1	10.0	-217.6	-129.3	-270.1	-248.0
12 Roro	Unitized	S	B -1,999 lm	15.0	-122.4	140.6	-198.3	-132.6	5.0	-186.3	76.7	-262.2	-196.5
12 Roro	Unitized	S	B -1,999 lm	10.0	-122.4	140.6	-198.3	-132.6	30.0	-186.3	76.7	-262.2	-196.5
12 Roro	Unitized	S	B -1,999 lm	5.0	-122.4	140.6	-198.3	-132.6	25.0	-186.3	76.7	-262.2	-196.5
12 Roro	Unitized	S	B -1,999 lm	30.0	-122.4	140.6	-198.3	-132.6	20.0	-186.3	76.7	-262.2	-196.5
12 Roro	Unitized	S	B -1,999 lm	25.0	-122.4	140.6	-198.3	-132.6	15.0	-186.3	76.7	-262.2	-196.5
12 Roro	Unitized	S	B -1,999 lm	20.0	-122.4	140.6	-198.3	-132.6	10.0	-186.3	76.7	-262.2	-196.5

Table A3-J: The Marginal Abatement Cost of Hull Coating 1 by ship type, size, and age

				2020	MAC low reduction potential		MAC high reduction potential		2030	MAC low reduction potential		MAC high reduction	
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate
13 Ferry	Passenger	S	A Pax Only, 25kn+	15.0	-208.5	189.8	-219.9	-120.3	5.0	-272.4	125.9	-283.8	-184.2
14 Ferry	Passenger	S	A Pax Only, 25kn+	10.0	-208.5	189.8	-219.9	-120.3	30.0	-272.4	125.9	-283.8	-184.2
15 Ferry	Passenger	S	A Pax Only, 25kn+	5.0	-208.5	189.8	-219.9	-120.3	25.0	-272.4	125.9	-283.8	-184.2
16 Ferry	Passenger	S	A Pax Only, 25kn+	30.0	-208.5	189.8	-219.9	-120.3	20.0	-272.4	125.9	-283.8	-184.2
17 Ferry	Passenger	S	A Pax Only, 25kn+	25.0	-208.5	189.8	-219.9	-120.3	15.0	-272.4	125.9	-283.8	-184.2
18 Ferry	Passenger	S	A Pax Only, 25kn+	20.0	-208.5	189.8	-219.9	-120.3	10.0	-272.4	125.9	-283.8	-184.2
13 Ferry	Passenger	S	B Pax Only, <25kn	15.0	-187.4	456.5	-214.6	-53.6	5.0	-251.3	392.6	-278.5	-117.5
14 Ferry	Passenger	S	B Pax Only, <25kn	10.0	-187.4	456.5	-214.6	-53.6	30.0	-251.3	392.6	-278.5	-117.5
15 Ferry	Passenger	S	B Pax Only, <25kn	5.0	-187.4	456.5	-214.6	-53.6	25.0	-251.3	392.6	-278.5	-117.5
16 Ferry	Passenger	S	B Pax Only, <25kn	30.0	-187.4	456.5	-214.6	-53.6	20.0	-251.3	392.6	-278.5	-117.5
17 Ferry	Passenger	S	B Pax Only, <25kn	25.0	-187.4	456.5	-214.6	-53.6	15.0	-251.3	392.6	-278.5	-117.5
18 Ferry	Passenger	S	B Pax Only, <25kn	20.0	-187.4	456.5	-214.6	-53.6	10.0	-251.3	392.6	-278.5	-117.5
13 Ferry	Passenger	S	C RoPax, 25kn+	15.0	-199.2	-140.1	-217.5	-202.7	5.0	-263.1	-204.0	-281.4	-266.6
13 Ferry	Passenger	S	C RoPax, 25kn+	10.0	-199.2	-140.1	-217.5	-202.7	30.0	-263.1	-204.0	-281.4	-266.6
13 Ferry	Passenger	S	C RoPax, 25kn+	5.0	-199.2	-140.1	-217.5	-202.7	25.0	-263.1	-204.0	-281.4	-266.6
13 Ferry	Passenger	S	C RoPax, 25kn+	30.0	-199.2	-140.1	-217.5	-202.7	20.0	-263.1	-204.0	-281.4	-266.6
13 Ferry	Passenger	S	C RoPax, 25kn+	25.0	-199.2	-140.1	-217.5	-202.7	15.0	-263.1	-204.0	-281.4	-266.6
13 Ferry	Passenger	S	C RoPax, 25kn+	20.0	-199.2	-140.1	-217.5	-202.7	10.0	-263.1	-204.0	-281.4	-266.6
13 Ferry	Passenger	S	D RoPax, <25kn	15.0	-174.9	-3.2	-211.5	-168.5	5.0	-238.8	-67.1	-275.4	-232.4
14 Ferry	Passenger	S	D RoPax, <25kn	10.0	-174.9	-3.2	-211.5	-168.5	30.0	-238.8	-67.1	-275.4	-232.4
15 Ferry	Passenger	S	D RoPax, <25kn	5.0	-174.9	-3.2	-211.5	-168.5	25.0	-238.8	-67.1	-275.4	-232.4
16 Ferry	Passenger	S	D RoPax, <25kn	30.0	-174.9	-3.2	-211.5	-168.5	20.0	-238.8	-67.1	-275.4	-232.4
17 Ferry	Passenger	S	D RoPax, <25kn	25.0	-174.9	-3.2	-211.5	-168.5	15.0	-238.8	-67.1	-275.4	-232.4
18 Ferry	Passenger	S	D RoPax, <25kn	20.0	-174.9	-3.2	-211.5	-168.5	10.0	-238.8	-67.1	-275.4	-232.4

Table A3-K: The Marginal Abatement Cost of Hull Coating 1 by ship type, size, and age

				2020	MAC low reduction potential		MAC high reduction potential		2030	MAC low reduction potential		MAC high reduction	
Category 1	Category 2	Category 3 (big or small)	Category 4 (size)	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate	Category 7 (ship remaining life time)	Low Estimate	High Estimate	Low Estimate	High Estimate
14 Cruise	Passenger	B	A 100,000+ gt	15.0	-179.8	144.2	-212.7	-131.7	5.0	-243.7	80.3	-276.6	-195.6
14 Cruise	Passenger	B	A 100,000+ gt	10.0	-179.8	144.2	-212.7	-131.7	30.0	-243.7	80.3	-276.6	-195.6
14 Cruise	Passenger	B	A 100,000+ gt	5.0	-179.8	144.2	-212.7	-131.7	25.0	-243.7	80.3	-276.6	-195.6
14 Cruise	Passenger	B	A 100,000+ gt	30.0	-179.8	144.2	-212.7	-131.7	20.0	-243.7	80.3	-276.6	-195.6
14 Cruise	Passenger	B	A 100,000+ gt	25.0	-179.8	144.2	-212.7	-131.7	15.0	-243.7	80.3	-276.6	-195.6
14 Cruise	Passenger	B	A 100,000+ gt	20.0	-179.8	144.2	-212.7	-131.7	10.0	-243.7	80.3	-276.6	-195.6
14 Cruise	Passenger	B	B 60-99,999 gt	15.0	-178.6	77.5	-212.4	-148.4	5.0	-242.5	13.6	-276.3	-212.3
14 Cruise	Passenger	B	B 60-99,999 gt	10.0	-178.6	77.5	-212.4	-148.4	30.0	-242.5	13.6	-276.3	-212.3
14 Cruise	Passenger	B	B 60-99,999 gt	5.0	-178.6	77.5	-212.4	-148.4	25.0	-242.5	13.6	-276.3	-212.3
14 Cruise	Passenger	B	B 60-99,999 gt	30.0	-178.6	77.5	-212.4	-148.4	20.0	-242.5	13.6	-276.3	-212.3
14 Cruise	Passenger	B	B 60-99,999 gt	25.0	-178.6	77.5	-212.4	-148.4	15.0	-242.5	13.6	-276.3	-212.3
14 Cruise	Passenger	B	B 60-99,999 gt	20.0	-178.6	77.5	-212.4	-148.4	10.0	-242.5	13.6	-276.3	-212.3
14 Cruise	Passenger	B	C 10-59,999 gt	15.0	-165.7	179.0	-209.2	-123.0	5.0	-229.6	115.1	-273.1	-186.9
14 Cruise	Passenger	B	C 10-59,999 gt	10.0	-165.7	179.0	-209.2	-123.0	30.0	-229.6	115.1	-273.1	-186.9
14 Cruise	Passenger	B	C 10-59,999 gt	5.0	-165.7	179.0	-209.2	-123.0	25.0	-229.6	115.1	-273.1	-186.9
14 Cruise	Passenger	B	C 10-59,999 gt	30.0	-165.7	179.0	-209.2	-123.0	20.0	-229.6	115.1	-273.1	-186.9
14 Cruise	Passenger	B	C 10-59,999 gt	25.0	-165.7	179.0	-209.2	-123.0	15.0	-229.6	115.1	-273.1	-186.9
14 Cruise	Passenger	B	C 10-59,999 gt	20.0	-165.7	179.0	-209.2	-123.0	10.0	-229.6	115.1	-273.1	-186.9
14 Cruise	Passenger	B	D 2-9,999 gt	15.0	-162.1	212.0	-208.3	-114.7	5.0	-226.0	148.1	-272.2	-178.6
14 Cruise	Passenger	B	D 2-9,999 gt	10.0	-162.1	212.0	-208.3	-114.7	30.0	-226.0	148.1	-272.2	-178.6
14 Cruise	Passenger	B	D 2-9,999 gt	5.0	-162.1	212.0	-208.3	-114.7	25.0	-226.0	148.1	-272.2	-178.6
14 Cruise	Passenger	B	D 2-9,999 gt	30.0	-162.1	212.0	-208.3	-114.7	20.0	-226.0	148.1	-272.2	-178.6
14 Cruise	Passenger	B	D 2-9,999 gt	25.0	-162.1	212.0	-208.3	-114.7	15.0	-226.0	148.1	-272.2	-178.6
14 Cruise	Passenger	B	D 2-9,999 gt	20.0	-162.1	212.0	-208.3	-114.7	10.0	-226.0	148.1	-272.2	-178.6
14 Cruise	Passenger	S	E -1,999 gt	15.0	-131.5	921.6	-200.6	62.7	5.0	-195.4	857.7	-264.5	-1.2
14 Cruise	Passenger	S	E -1,999 gt	10.0	-131.5	921.6	-200.6	62.7	30.0	-195.4	857.7	-264.5	-1.2
14 Cruise	Passenger	S	E -1,999 gt	5.0	-131.5	921.6	-200.6	62.7	25.0	-195.4	857.7	-264.5	-1.2
14 Cruise	Passenger	S	E -1,999 gt	30.0	-131.5	921.6	-200.6	62.7	20.0	-195.4	857.7	-264.5	-1.2
14 Cruise	Passenger	S	E -1,999 gt	25.0	-131.5	921.6	-200.6	62.7	15.0	-195.4	857.7	-264.5	-1.2
14 Cruise	Passenger	S	E -1,999 gt	20.0	-131.5	921.6	-200.6	62.7	10.0	-195.4	857.7	-264.5	-1.2

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APPENDIX IV

MARGINAL ABATEMENT COST CURVES

A4.1 Appendix IV shows the MACC of other ships in 2020 other than crude tankers, bulkers, and containerships (these are included in Chapter 6). Figures A4 1-12 are aggregated MACC for all ships, new build and existing. Figures A4 13- 22 are MACC for new build ships only.

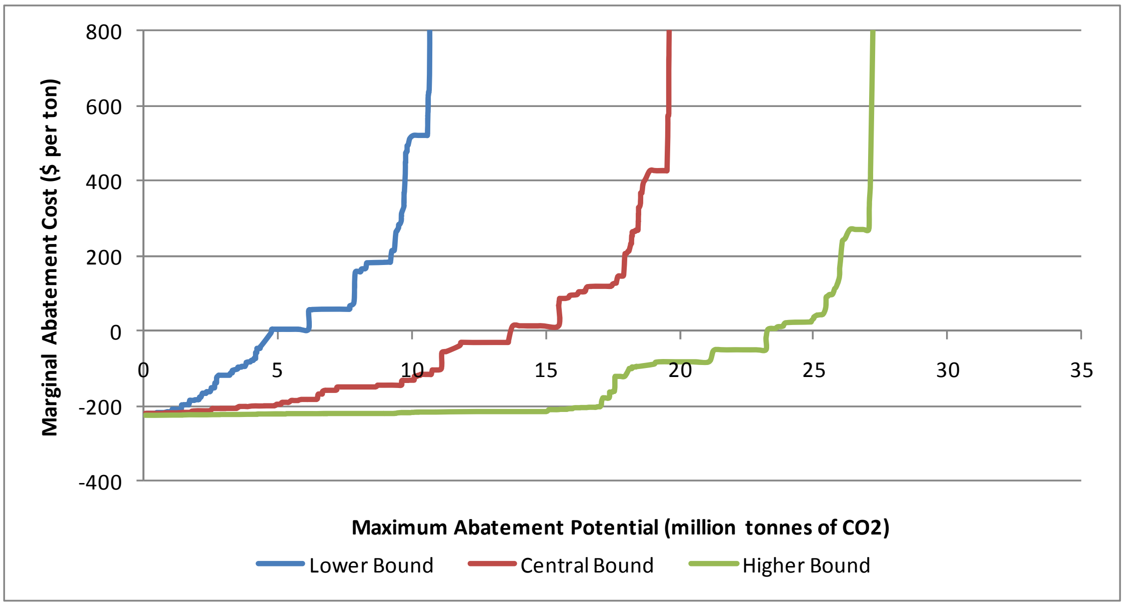

Figure A4-1: Aggregated MACC for product tankers in 2020

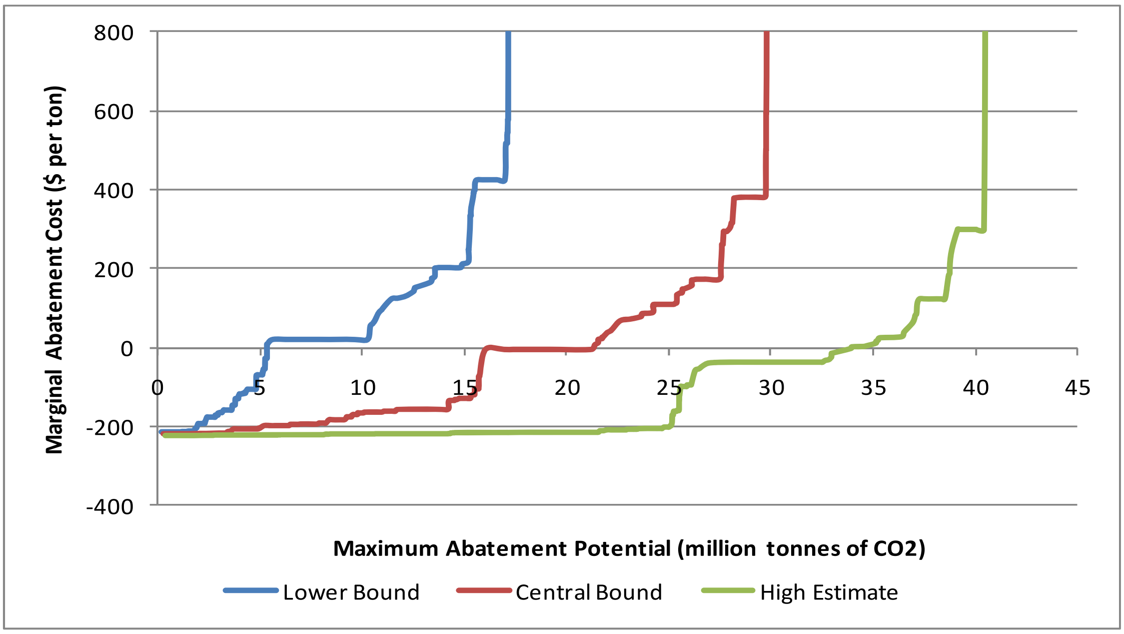

Figure A4-2: Aggregated MACC for chemical tankers in 2020

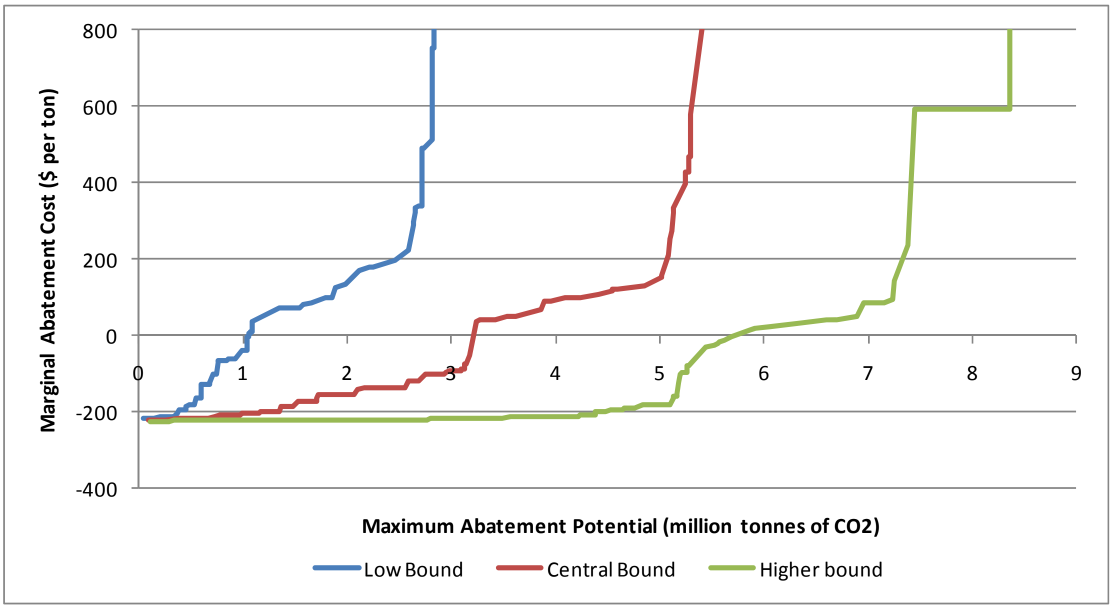

Figure A4-3: Aggregated MACC of LPG ships in 2020

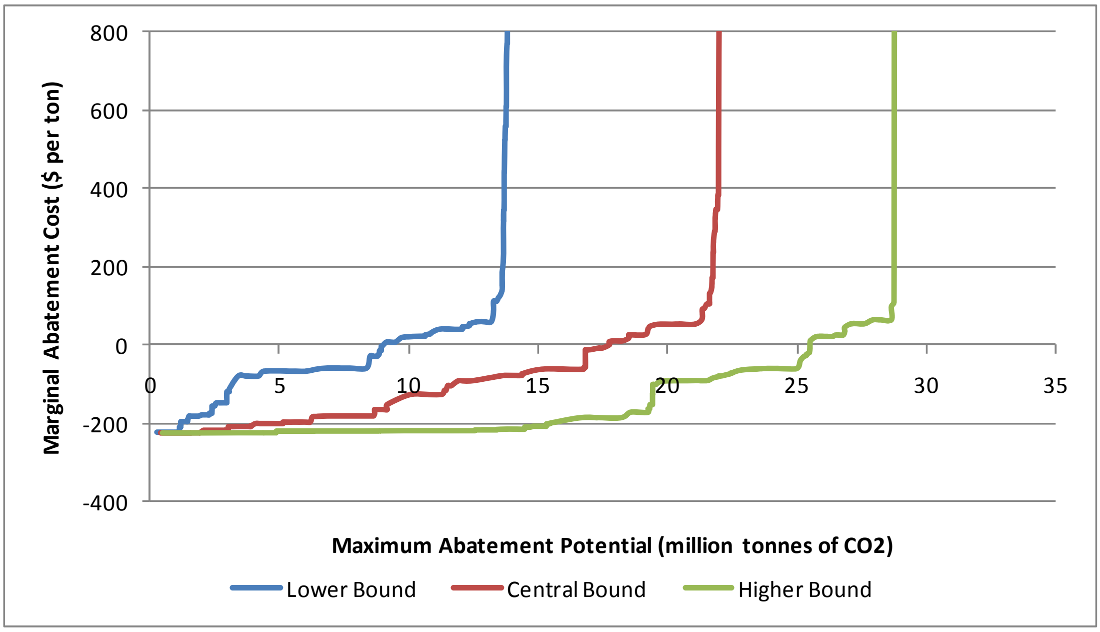

Figure A4-4: Aggregated MACC of LNG ships in 2020

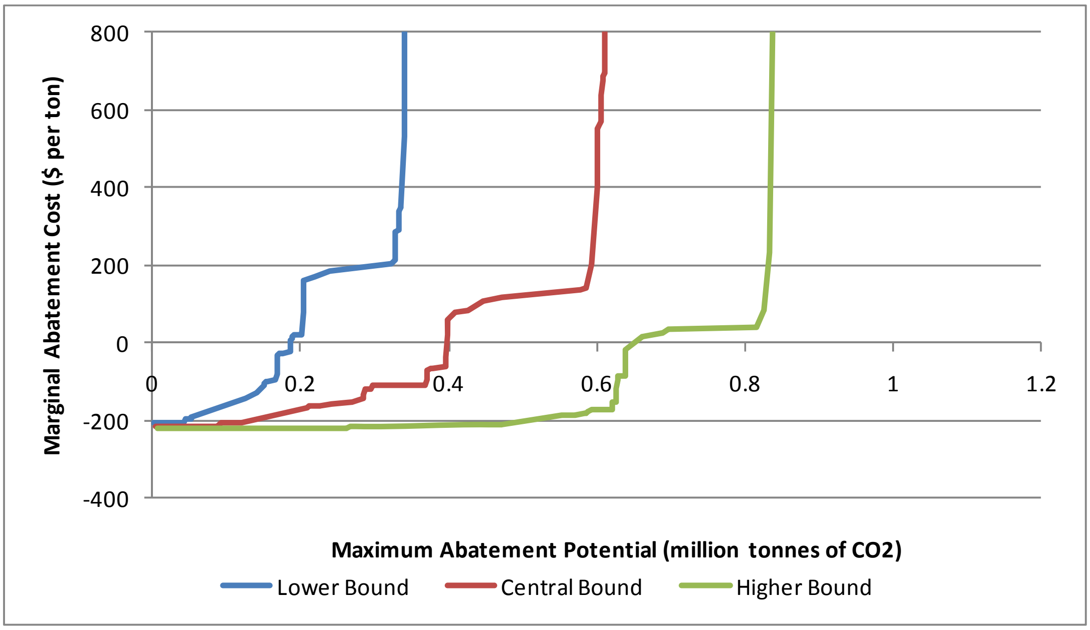

Figure A4-6: Aggregated MACC of other tankers in 2020

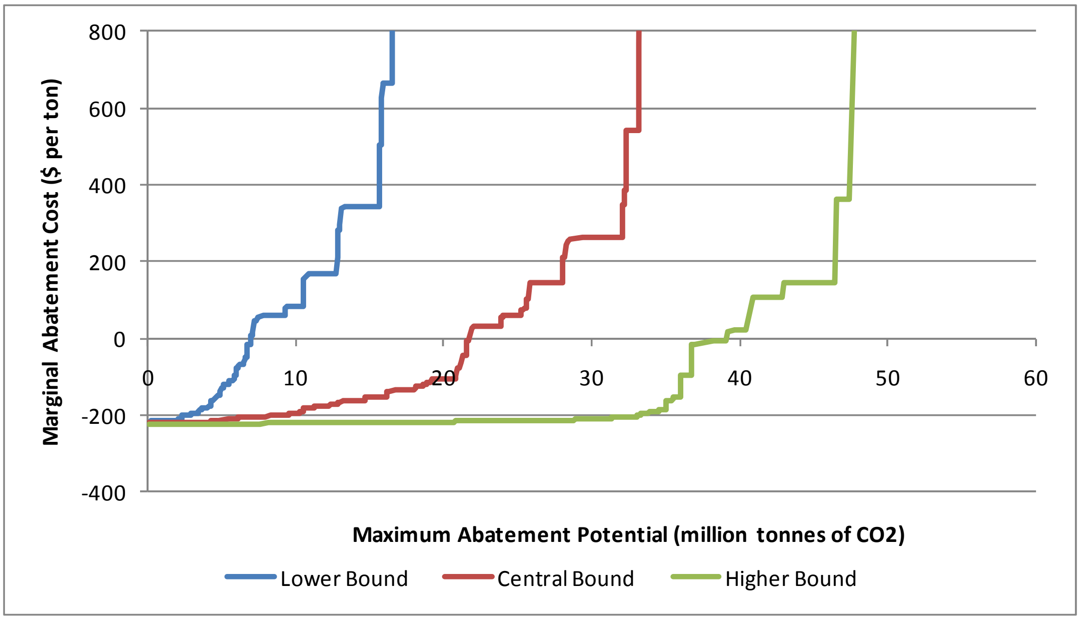

Figure A4-7: Aggregated MACC of general cargo ships in 2020

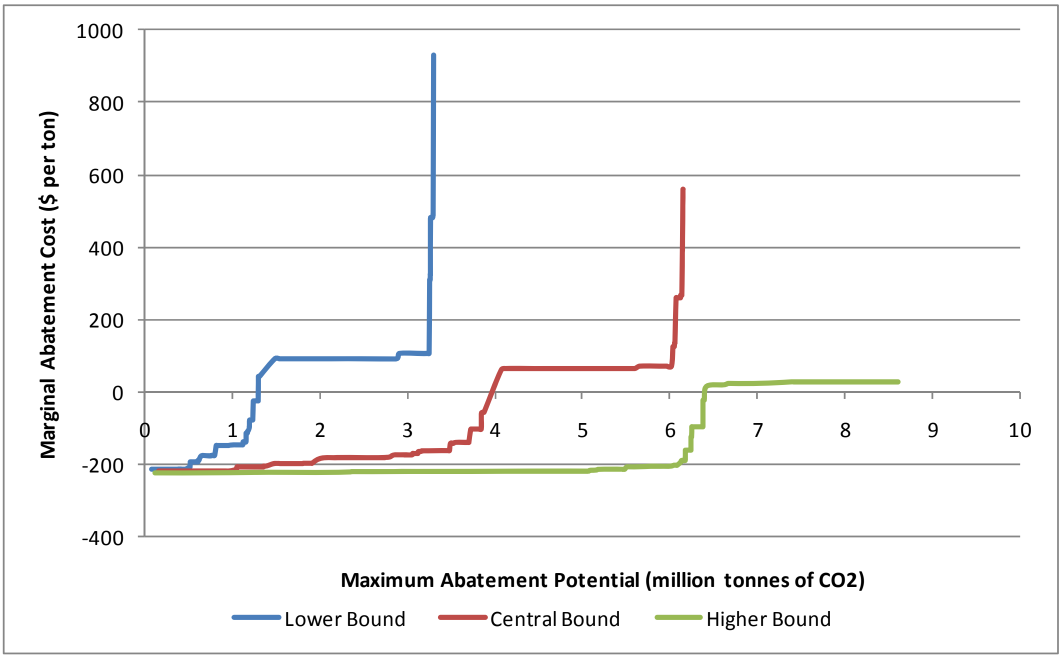

Figure A4-8: Aggregated MACC of other dry cargo ships in 2020

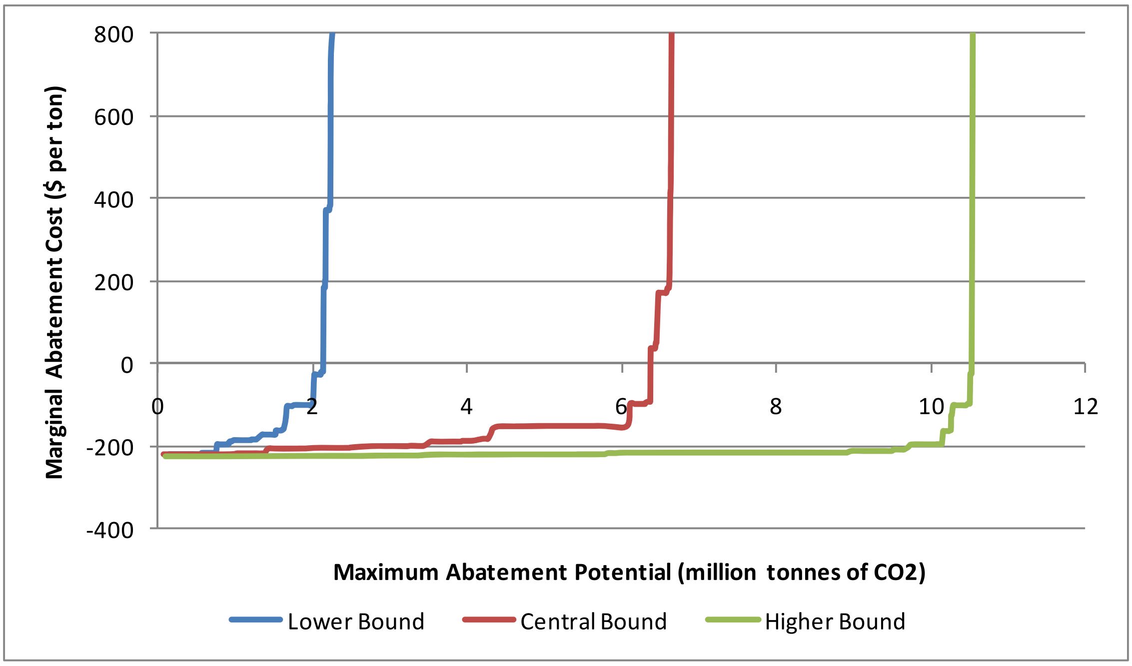

Figure A4-9: Aggregated MACC of vehicles ships in 2020

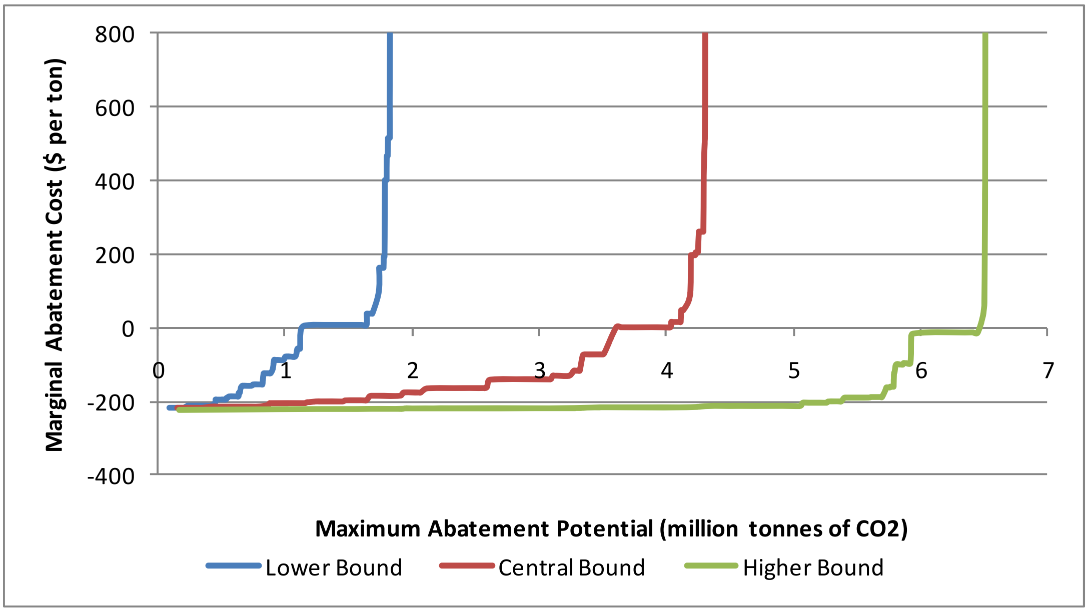

Figure A4-10: Aggregated MACC of RoRos in 2020

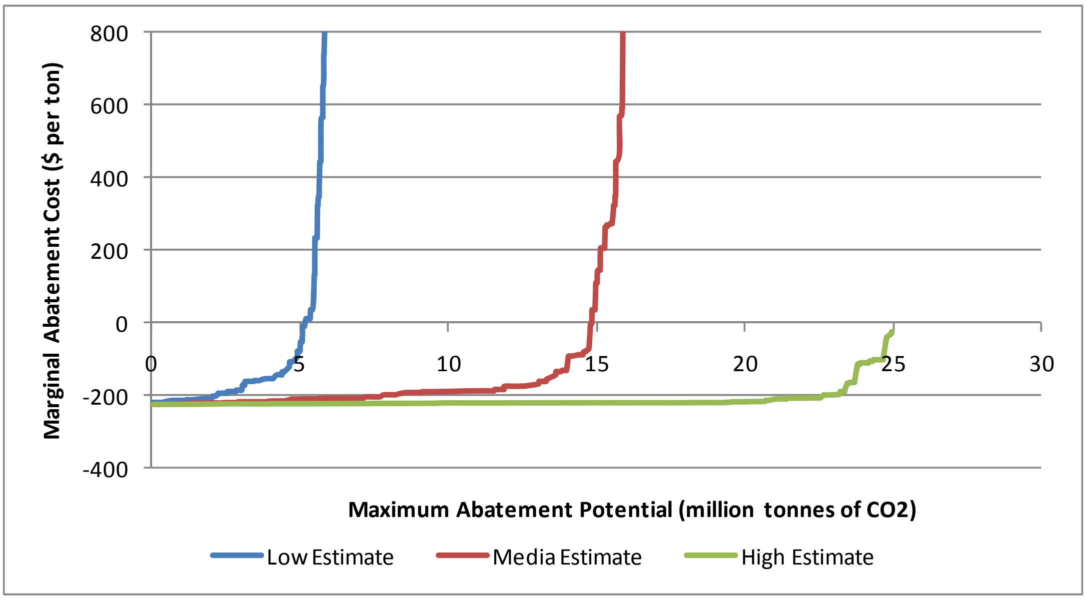

Figure A4-11: Aggregated MACC of Ferries in 2020

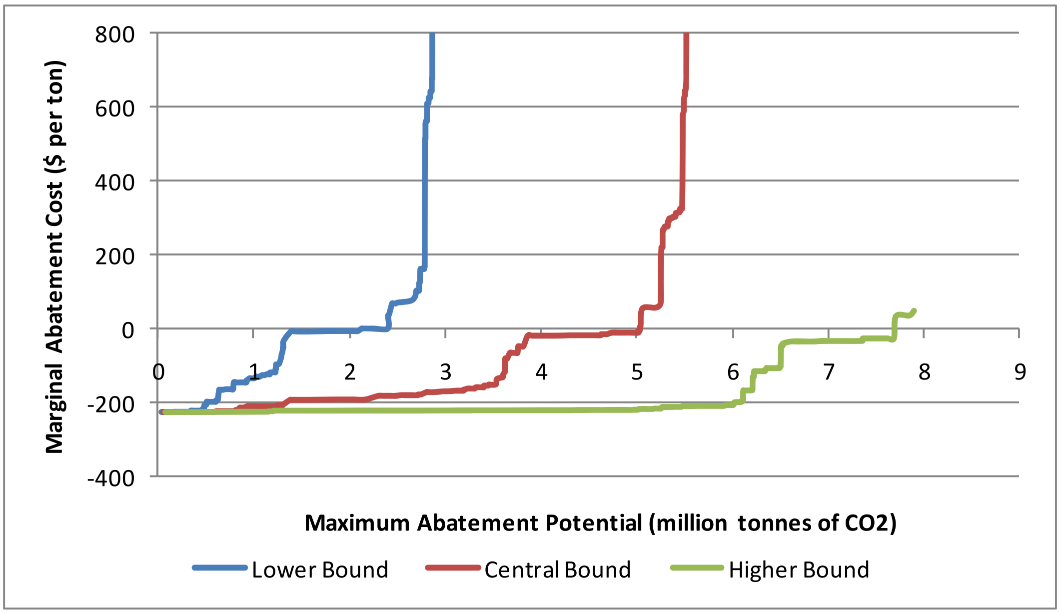

Figure A4-12: Aggregated MACC of Cruise ships in 2020

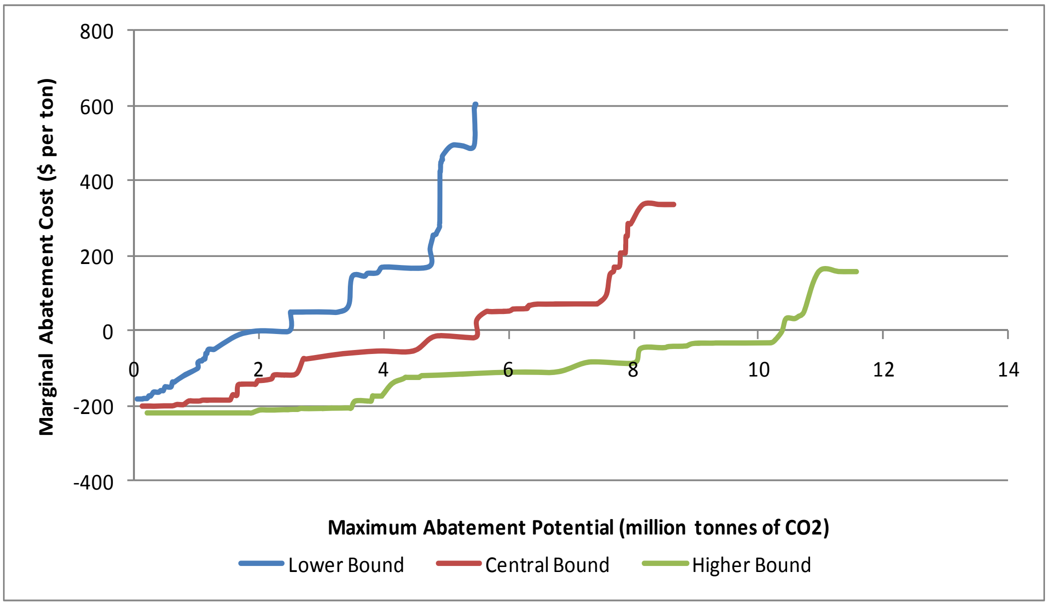

Figure A4-13: Aggregated MACC of new build product tankers in 2020

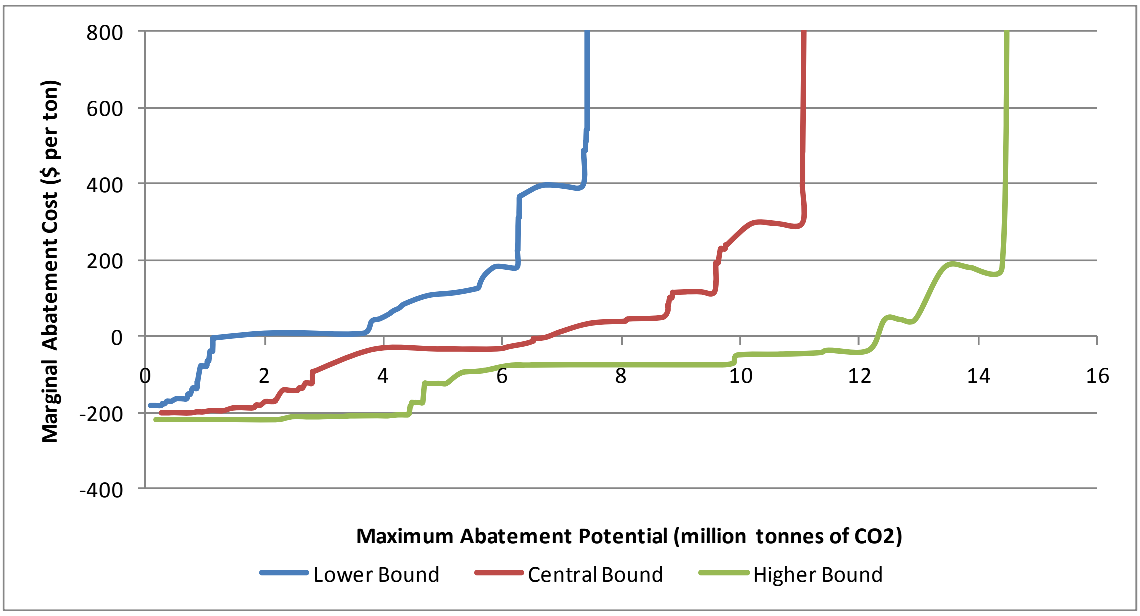

Figure A4-14: Aggregated MACC of new build chemical in 2020

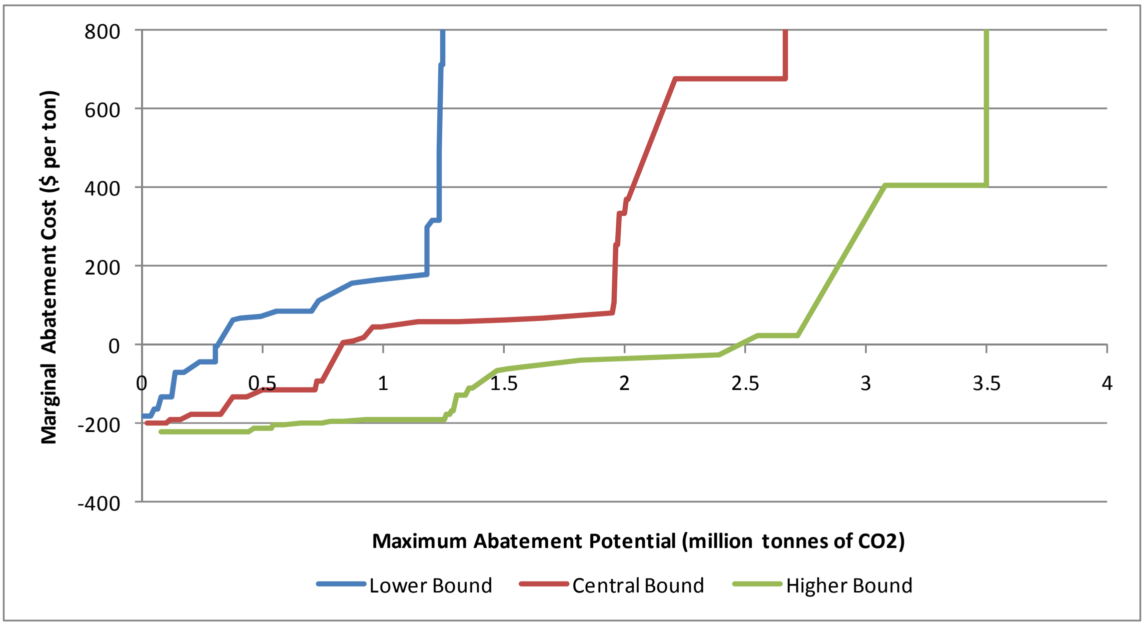

Figure A4-15: Aggregated MACC of new build LPG ships n 2020

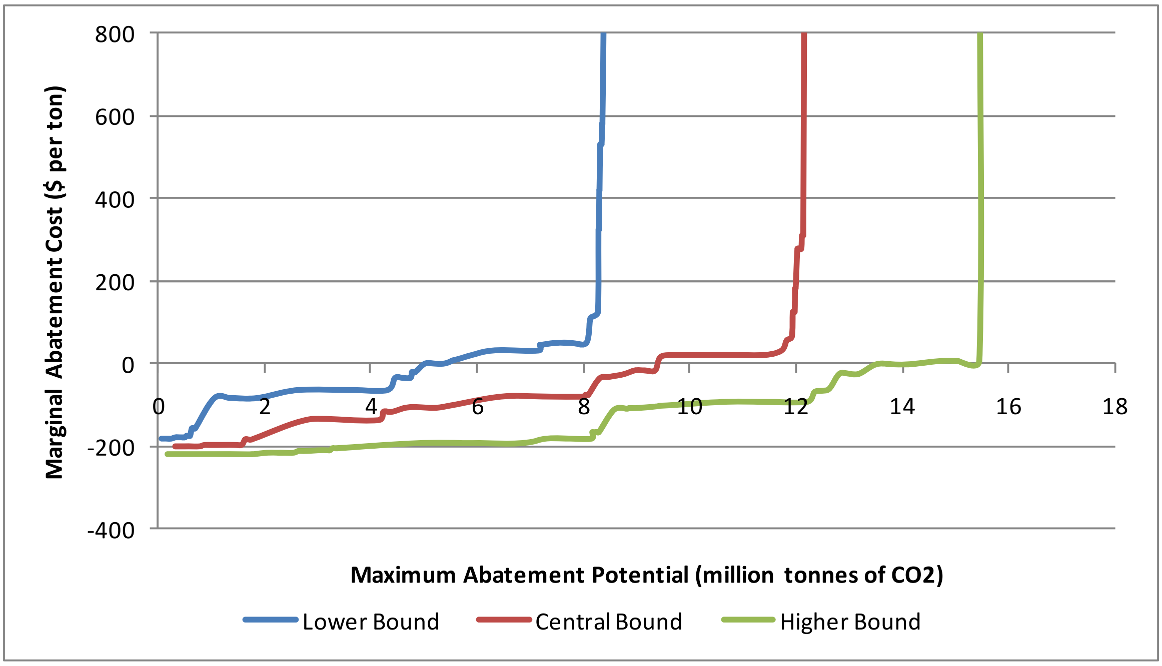

Figure A4-16: Aggregated MACC of new build LNG ships in 2020

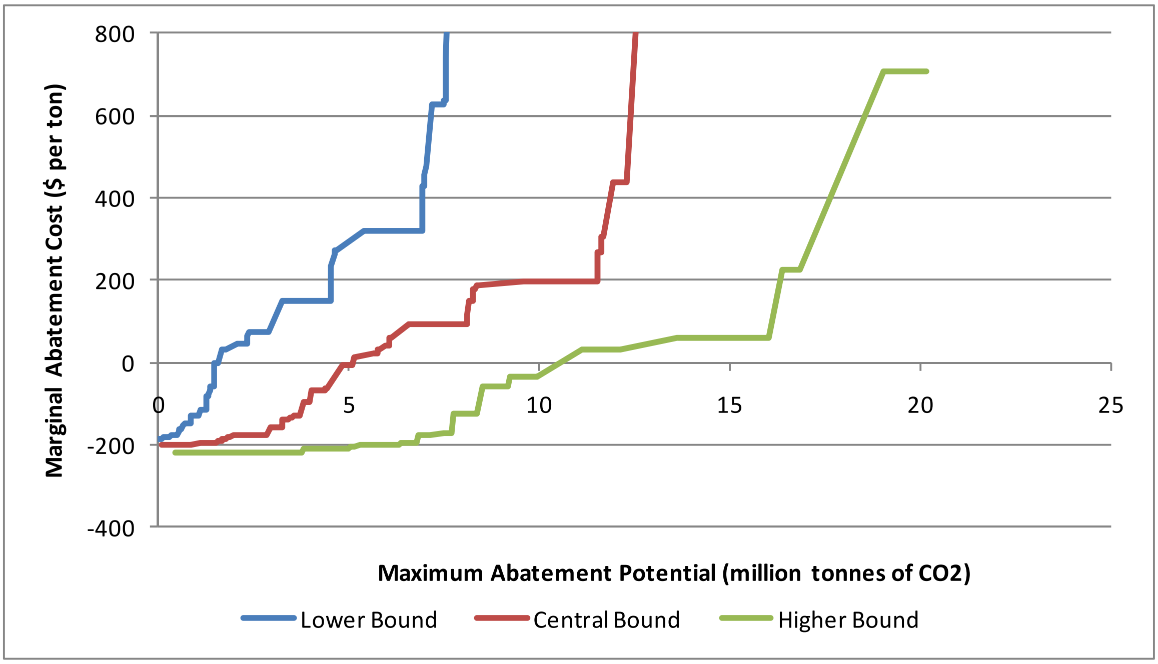

Figure A4-17: Aggregated MACC of new build general cargo ships in 2020

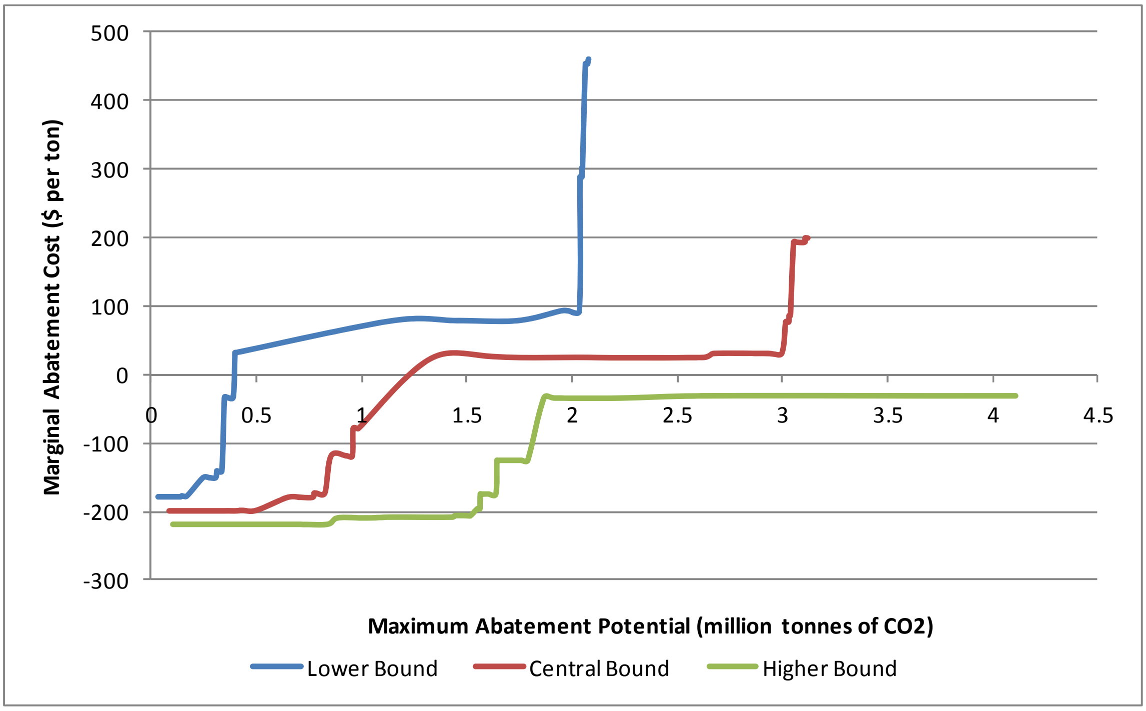

Figure A4-18: Aggregated MACC of new build other dry ships in 2020

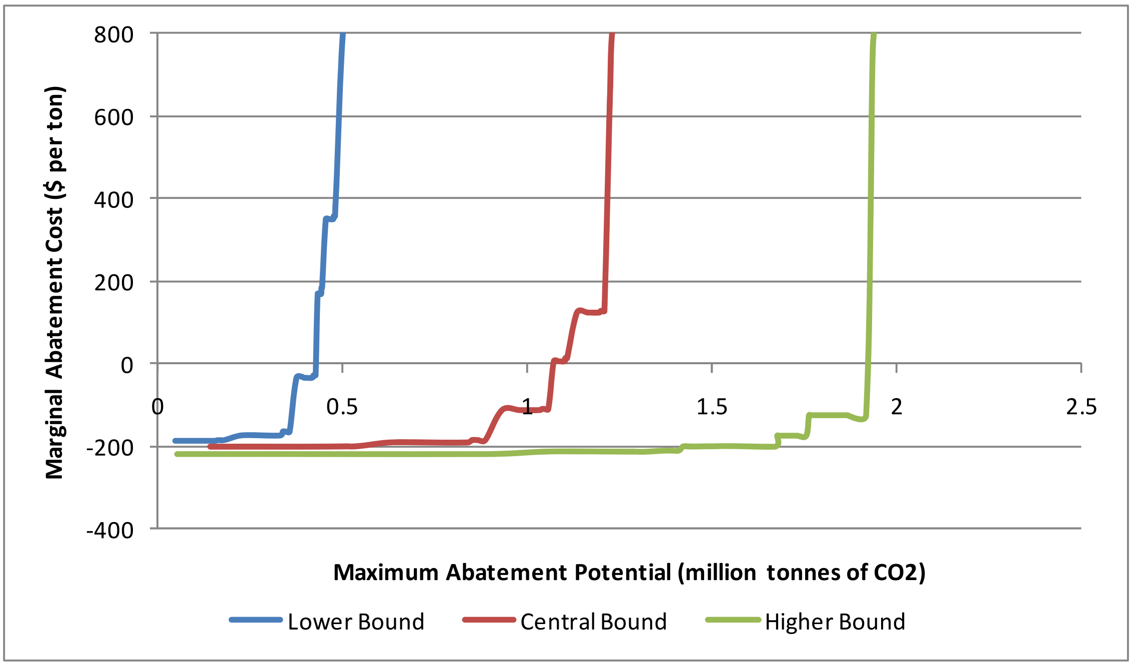

Figure A4-19: Aggregated MACC of new build vehicle ships in 2020

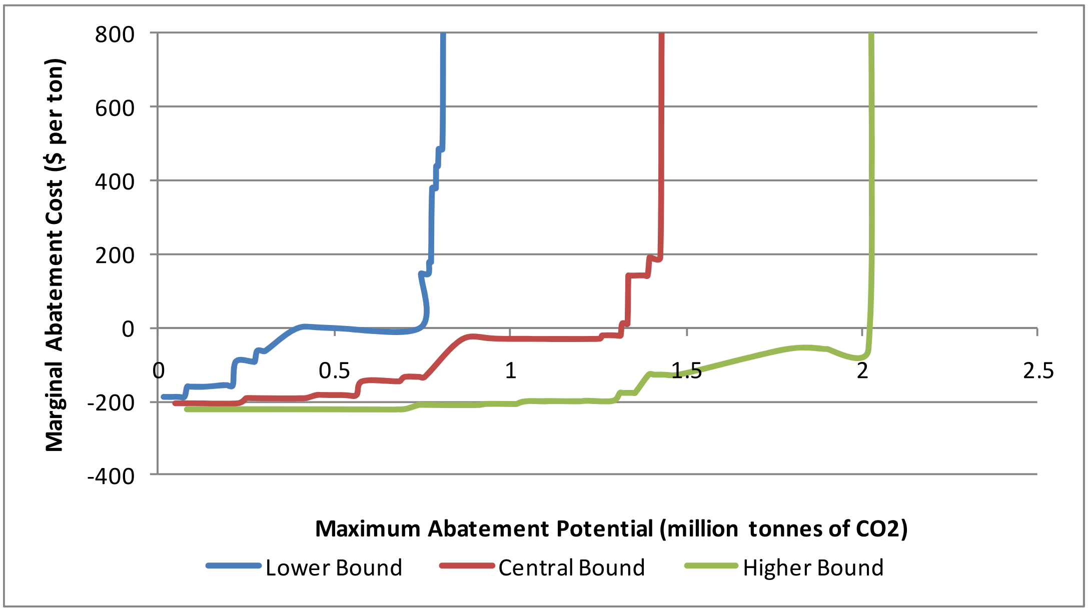

Figure A4-20: Aggregated MACC of new build RoRo ships in 2020

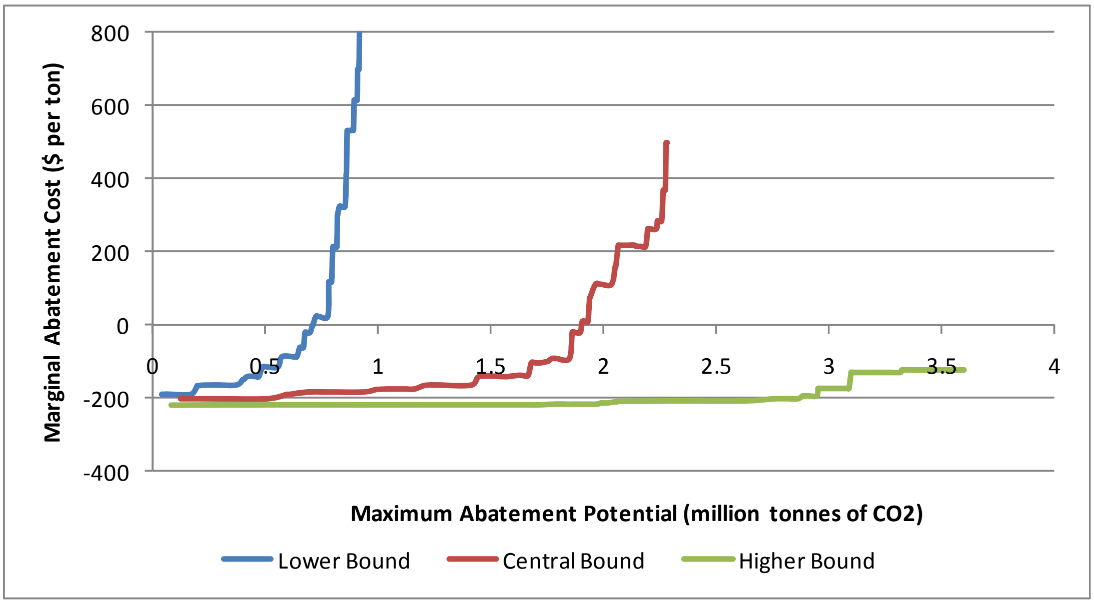

Figure A4-21: Aggregated MACC of new build Ferries in 2020

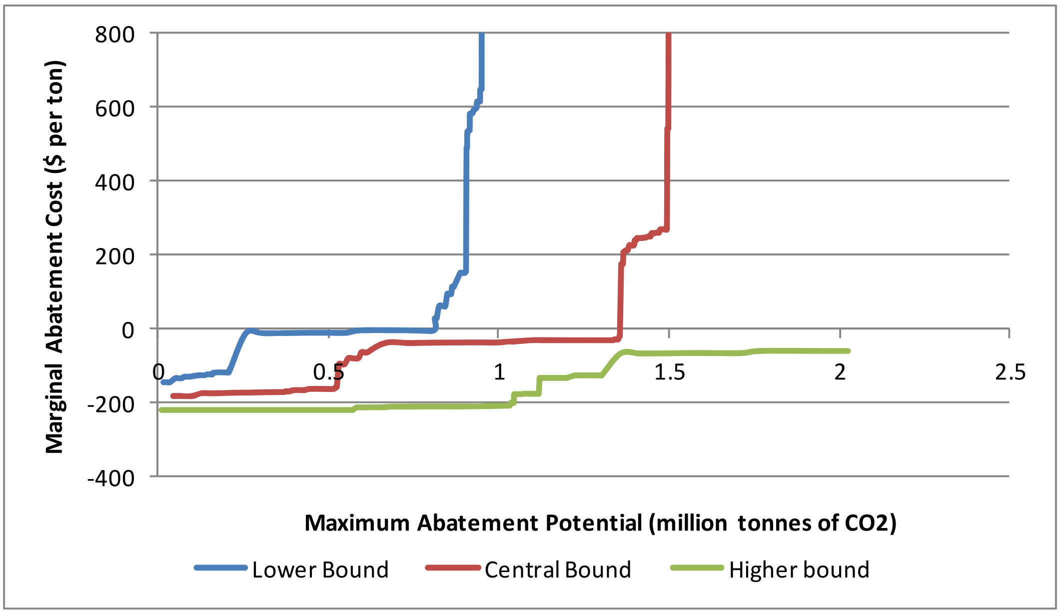

Figure A4-22: Aggregated MACC of new build Cruise ships in 2020

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