Analysis of GHG Marginal Abatement Cost Curves

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Preface

This report was written by CE Delft and Marena Ltd for the Ocean and Policy Research Foundation. The authors want to thank the interviewees from shipping companies and other maritime stakeholders for their willingness to co-operate in this project. We would also like to thank Tore Longva of DNV for providing details on the methodology of their Marginal Abatement Cost Curve. Of course, all eventual errors and shortcomings can only be attributed to the authors.

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Summary

Greenhouse gas emissions from maritime transport account for approximately 3% of global emissions and are projected to increase rapidly over the next decades. One of the ways to reduce these emissions is to improve the fuel efficiency of ships. Many measures can be implemented to do so, ranging from weather routing to installing solar cells.

Marginal abatement cost curves (MACC) present measures to reduce GHG emissions in order of their cost-effectiveness. Over the last years, several MACCs have been published that appear to project different abatement potentials. One thing the MACCs have in common is that they project a large cost-effective potential: several measures can be implemented at a net profit.

This report has analysed the different MACCs and finds that their differences can be explained to a large extent by the fact that they use different emission baselines and a slightly different set of measures. Other factors that contribute to the differences are small differences in the costs and potentials of specific measures, and differences in the projected fleet structure.

The differences in the cost-effectiveness of the most profitable options are caused predominantly by different assumptions about future fuel prices. Different assumptions on discount rates have a smaller impact.

This report presents a literature survey and reports on interviews that aim to analyse the reasons for the existence of a cost-effective abatement potential. There are three main reasons why not all cost-effective measures are taken:

1. Technological barriers. Not all the technologies that appear in the MACCs are considered to yield fuel savings by the ship owners and operators interviewed. Moreover, some technologies are perceived to be associated with a high risk of failure.
2. Institutional barriers. Two institutional barriers are of particular importance. The first is the fact that currently, neither charter rates nor second hand prices of ships reflect its fuel efficiency. This means that ship owners who invest in fuel efficiency improving measures cannot, in general, recoup their investment, unless they operate their own ships or have long term agreements with charterers. The second is that many yards do not have the capacity to offer changes to existing designs, or are only willing to do so against substantial costs. Many yards seem to have focussed on bringing newbuilding costs down, with little regard to lifecycle costs.
3. Financial barriers. The main financial barrier appears to be associated with the risk of certain technologies.

In the future, some of the institutional barriers may be lowered as EEDI and other measures of efficiency and broader environmental performance become standardised. These could potentially have the effect that more of the investments can be recouped by higher charter rates or second hand prices for better ships.

1 Introduction

Greenhouse gas emissions from maritime transport account for approximately 3% of global emissions and are projected to increase rapidly over the next decades (IMO, 2009). In order to reduce impact shipping has on climate, several policies have been proposed. Within the International Maritime Organization (IMO), operational, technical and market based instruments are being discussed.

In the evaluation of these proposals, cost-effectiveness and the impact on the shipping sector are important criteria. One way in which these can be assessed is through the use of Marginal Abatement Cost Curves (MACCs). These curves indicate how the marginal cost-effectiveness depends on the amount of emissions being reduced, relative to a baseline. Insofar as these curves identify specific technologies, they give an indication of the technologies that can be used to reach a certain emissions target in the most cost-effective manner.

Over the past years, four MACCs of the shipping sector have been published:

- IMO (2009), 2nd IMO GHG Study 2009, London.
- DNV (2010), Pathways to low carbon shipping/Eide et al. (2011), Future cost scenarios for reduction of ship CO_2 emissions.
- IMAREST (2010a), Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures, MEPC 61/INF. 18. And
- CE et al. (2009), Technical support for European action to reducing Greenhouse Gas Emissions from international maritime transport.

In addition, the Ocean Policy Research Foundation (OPRF) is developing a MACC for shipping, which is mainly based on the analysis by the Japanese administration for EEDI. In this work, the OPRF envisages to compare its MACC to other MACCs that have been recently published. Such a comparison is not straightforward, however, as MACCs are a function of many variables, including fuel prices and discount rates. This report aims to provide a comparative analysis of the published MACCs.

Most MACCs of shipping indicate that there is a considerable potential to improve the efficiency of ships cost-effectively and that this potential will grow in the coming decades. From a conventional economic point of view, this can only be the case if there are barriers to the implementation of these measures that are larger than the potential profits. This report aims to identify these barriers and estimate their relevance.

1.1 Objective

The objective of this report is twofold:
1. Provide a comparative analysis of the various marginal abatement cost curves for shipping that have been published over the last years.
2. Identify barriers to the implementation of cost-effective measures to reduce GHG emissions and/or improve the fuel efficiency of ships.

1.2 Outline

Chapter 2 provides a comparative analysis of the published MACCs based on a comparison of the underlying assumptions and on an interview with the author of one of the reports. Chapter 2.5 analyses the barriers to the implementation of cost-effective measures to improve the fuel efficiency of ships. It is based on a literature review and on interviews with stakeholders. Chapter 4 concludes.

2 Comparison of MACCs

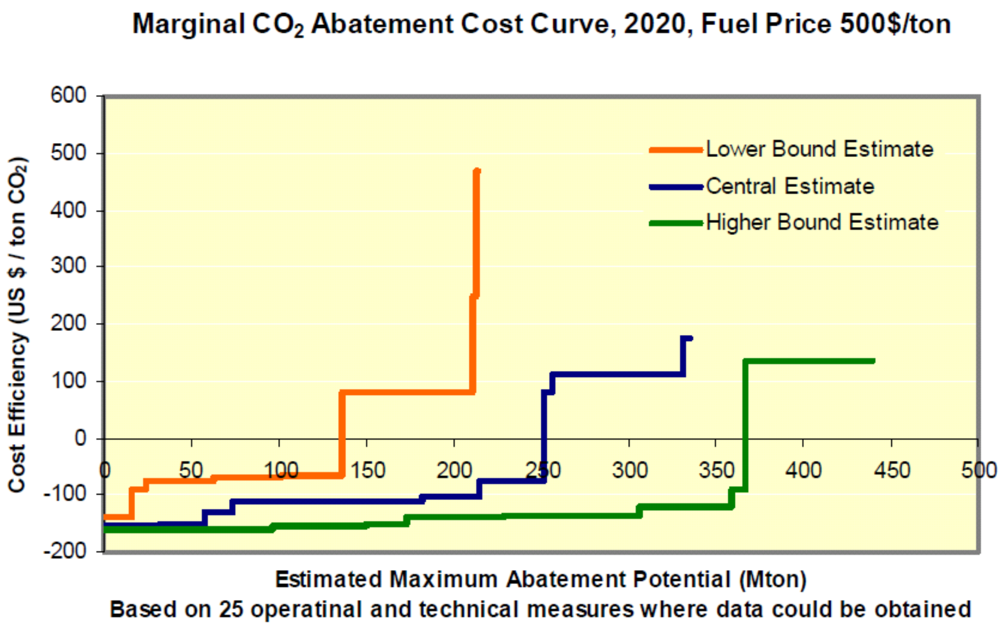
2.1 Overview of published MACCs

To our knowledge, four Marginal CO_2 Abatement Cost Curves of the maritime shipping sector have been published in recent years:

- IMO (2009), 2nd IMO GHG Study 2009, London (Figure 1).
- DNV (2010), Pathways to low carbon shipping (Figure 2)/Eide et al. (2011), Future cost scenarios for reduction of ship CO_2 emissions.
- IMAREST (2010a), Marginal Abatement Costs and Cost Effectiveness of Energy-Efficiency Measures, MEPC 61/INF. 18 (Figure 3). And
- CE et al. (2009), Technical support for European action to reducing Greenhouse Gas Emissions from international maritime transport (Figure 4).

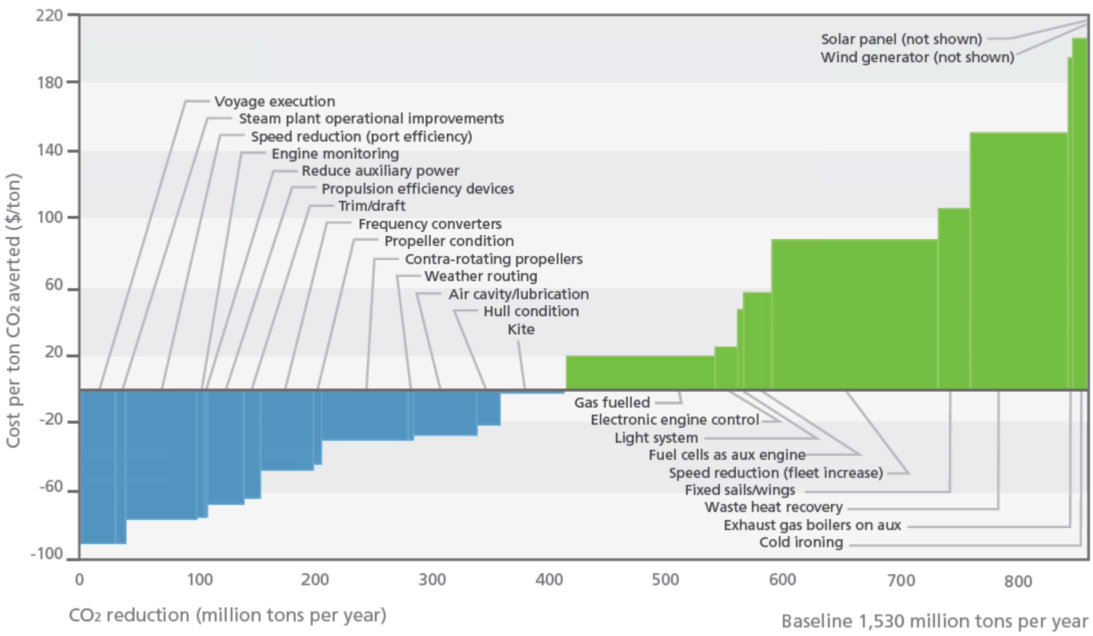
In addition, MACCs have been published in a Norwegian submission to MEPC, IMAREST (2010b) (Updated Marginal Abatement Cost Curves for shipping) and in Annex 10 to the *Full report of the work undertaken by the Expert Group on Feasibility Study and Impact Assessment of possible Market-based Measures* (MEPC 61/INF.2). Both of these were made using the same DNV database as Eide et al. (referenced above) and are therefore not included in the analysis.

Figure 1 Indicative marginal CO_2 abatement costs for 2020



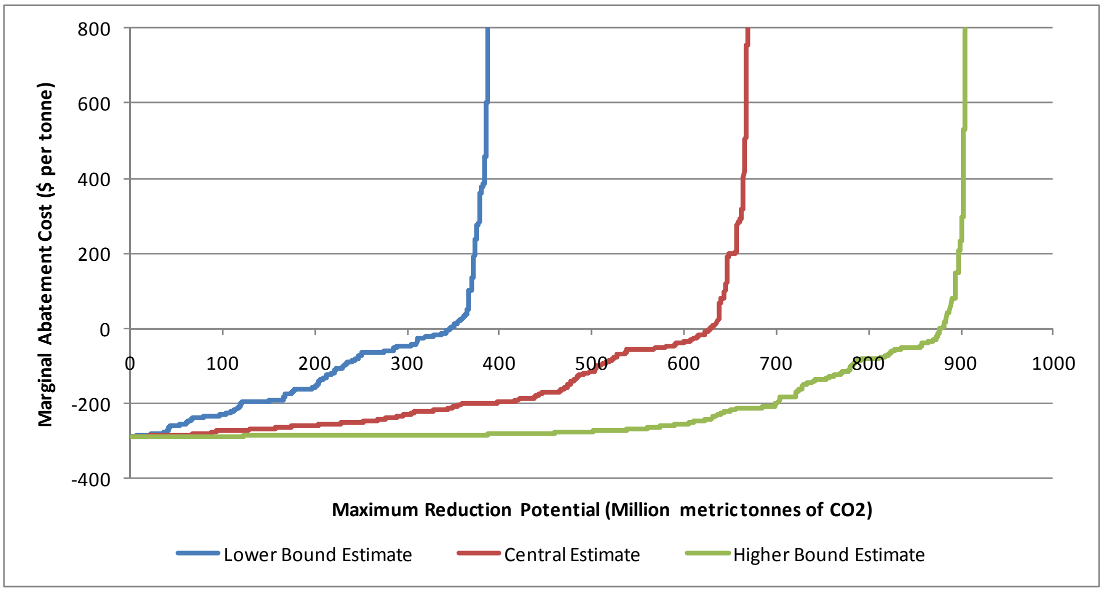
Source: IMO, 2009.

Figure 2 Average Marginal CO_2 Reduction Cost Per Option - World Shipping Fleet In 2030



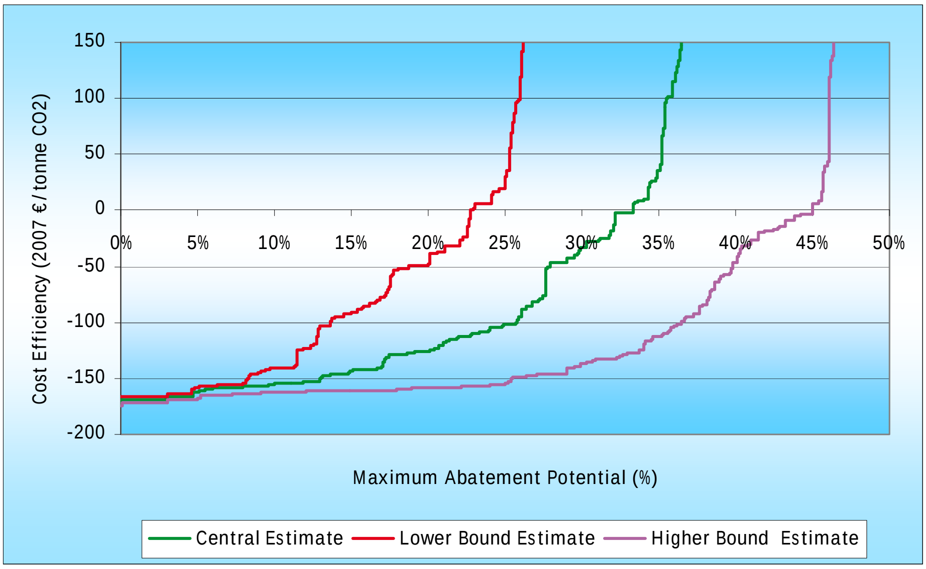
Source: DNV, 2010; Pathways to low carbon shipping. Abatement potential towards 2030.

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



Source: IMAREST, 2010a.

Figure 4 **Marginal CO_2 Abatement Costs for the Maritime Transport Sector in 2030 relative to frozen-technology scenario, Range of Estimates, US$ 700/tonne fuel, 9% Interest Rate**



Source: CE et al., 2009.

Previous analysis has shown that MACCs are sensitive to numerous assumptions. The most important assumptions are (IMAREST, 2010a):

- The projected price of fuel.
- The projected fleet.
- The projected fleet renewal rate.
- The abatement measures included in the MACC.
- The discount rate.
- The efficiency of the current fleet.
- The uptake of technologies in the current fleet.
- The future uptake of technologies.

For each of the MACCs studied, we have retrieved the assumptions. We have also assess the extent to which differences in assumptions can explain the differences in the MACCs.

2.2 Descriptive comparison

To our knowledge, the MACC published in IMO (2009) has been the first MACC for shipping. It has been derived in a collaborative effort of MARINTEK, CE Delft and DNV. The other three MACCs are based on this one.

The main differences between the MACC presented in IMO (2009) and the other MACCs are, first, the year of consideration, namly 2020 and not 2030, and, second, the resolution. Whereas the former is presented for fleet average cost-effectiveness values of a limited number of technologies, the latter three include a larger number of technologies and calculate cost-effectiveness for a large number of ship type and size categories. In the following we will compare the three MACCs for 2030, i.e. the MACCS published by Eide et al. (2011), IMAREST (2010a) and CE et al. (2009).

2.2.1 Abatement potential

Table 1 shows a comparison of the main MACCs on both cost-effective and maximum relative abatement potential.

Table 1 Comparison of cost-efficient and maximum relative abatement potential

	Eide et al. (2011)	IMAREST (2010a)	CE et al. (2009)
Fuel price in 2030	HFO, LNG: 350 USD/t MDO: 500 USD/t	700 USD/t*	350 USD/t
Discount rate	8% **	10%	9%
Cost-effective relative abatement potential in 2030	~30%	~27%	~25%
Maximum relative abatement potential in 2030	~56%	~34%	~37%

* This is a scenario presented in the sensitivity analysis; in the main scenario a fuel price of 900 USD/t is used.

** This is a scenario presented in the sensitivity analysis; in the main scenario a discount rate of 5% is used and the cost-efficient reduction potential is 11% higher.

In Table 1 the cost-effective and maximum relative abatement potentials derived in the different studies are given for the most comparable scenario.

The cost-effective relative abatement potential in 2030 is assessed to be slightly lower in IMAREST (2010a) and CE et al. (2009) compared to Eide et al. (2011) and the maximum relative abatement potential in 2030 is assessed to be significantly higher in Eide et al. (2011) than in IMAREST (2010a) and in CE et al. (2009).

2.2.2 Framework for the comparative analysis

There are five main factors that determine a Marginal Abatement Cost Curve:
1. The methodology.
2. The scope of the study.
3. The data of the base year.
4. The disaggregation level.
5. Expectations/projections.

These elements are all taken into account in the comparative analysis of the MACCs in Section 2.3. They are illustrated briefly below.

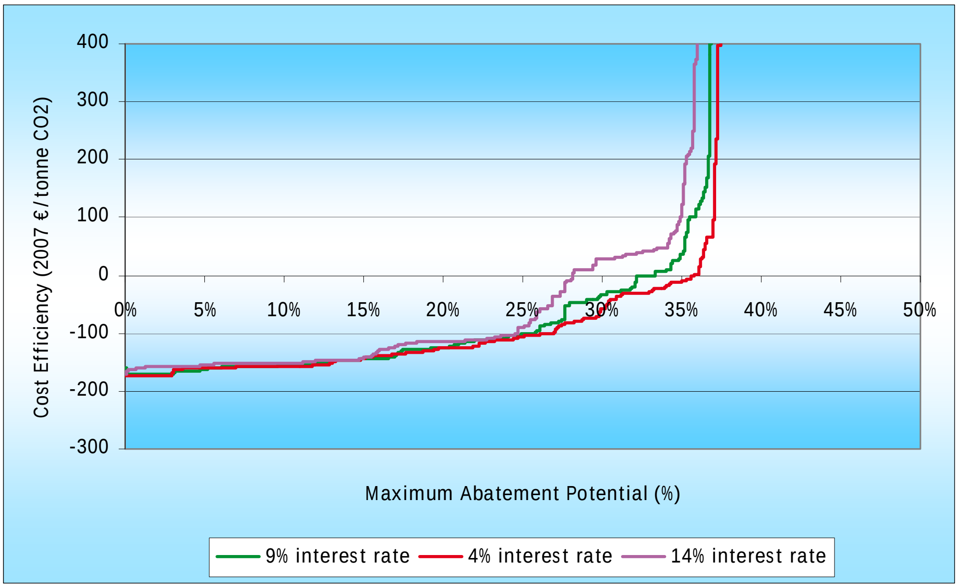
Methodology

There are four major methodological choices to be made when setting up a Marginal Abatement Cost Curve. Choices have to be made regarding:

1. Whether a social or business perspective is taken.
2. Whether and how the abatement measures interact.
3. Whether a frozen technology emission baseline is chosen or a baseline that takes an autonomous efficiency improvement into account. And
4. Which measures are included in the analysis.

A MACC can be set up from two different perspectives, a social or a business perspective. This is mainly reflected in the level of the discount rate that is used to determine the costs that are associated with an abatement measure. The discount rate is higher when a private perspective is chosen, reflecting the fact that companies pay higher interest rates than states. A lower discount rate results in a higher cost-effective abatement potential. The sensitivity analysis carried out in CE et al. (2009) shows that there is indeed a change in the cost-effective abatement potential but that this change can be relatively small:

Figure 5 **Sensitivity analysis w.r.t. discount rate**



Source: CE et al., 2009.

There are CO_2 abatement measures that are not likely to be adopted at the same time or measures that even exclude each other. The abatement potential is overestimated if it is assumed that those measures can be used at large. But even when it is taken into account that not all measures are relevant when determining the abatement potential, MACCs could differ inasmuch as different adoption behaviour can be presumed: different criteria can be used when modelling the choice of the abatement measure from a group of measures that exclude each other. It can, for instance, be assumed that the measure with most advantageous cost-effectiveness will be applied, irrespective of its abatement potential. Alternatively, it could be assumed that the measure with the highest profits or lowest costs is chosen.

The emission baseline can either be modelled as a frozen technology baseline or as an emission baseline with an autonomous efficiency improvement. Whereas absolute and relative abatement potential presented in the MACC are higher when a frozen technology baseline is used, the emission level that, irrespective of the costs, could be achieved should be the same under both approaches. However, the costs for achieving a certain emission level will be assessed different under these two approaches.

When the probability that an abatement measure will be applied to a ship type/size category is rather low, one might choose not to take this abatement potential into account at all or, alternatively, to take this relative low abatement potential against relative high costs into account. This choice will have an impact on the maximum but not on the cost-effective abatement potential.

Scope of Study

The course of a MACC is further determined by the:

- Segment of the world fleet under consideration.
- Ship types considered.
- Ship sizes considered (threshold value). And
- The types of abatement measure that are taken into account (operational and/or technological, established and/or innovative, design and/or retrofit).

Data of base year

The data that is used/is available for the base year is of course crucial for the run of the MACC too. Data is needed w.r.t.:

- The fleet (fuel consumption and (age) structure).
- Costs of abatement measures.
- Reduction potential of measures.
- Diffusion rate of abatement measures.

Disaggregation level

The MACC will have a different run, depending on the disaggregation level with which is worked for setting up the curve. Data can be differentiated w.r.t.:

- Ship type/size categories.
- Age structure.
- Differentiation of cost and reduction potential data w.r.t. the above mentioned categories.

When abatement measures can only be applied to specific ship types and/or size categories, the abatement potential is difficult to determine when aggregated fleet data are used. The cost efficiency of a certain abatement measures for the average fleet can also deviate strongly from the cost efficiency for particular fleet segment.

Working with an age structure of a fleet allows, on the one hand, to predict more precisely the number of new ships that enter the market, and allows on the other hand to determine the number of relative old ships in the fleet. The more new ships enter the fleet, the higher the autonomous efficiency improvement. Relative old ships cannot be expected to invest in retrofit measures that have a relative long payback time.

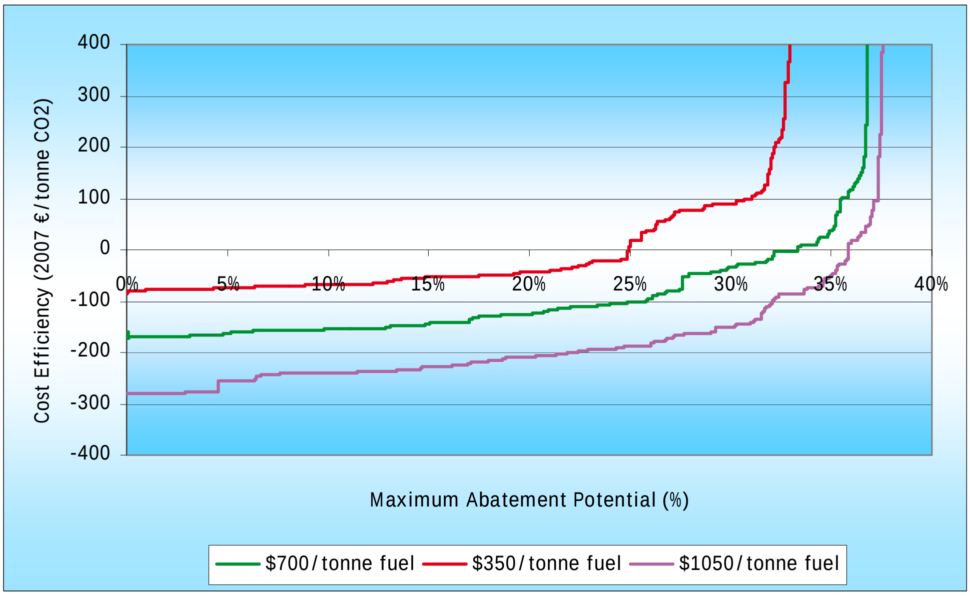
Expectations/projections

The expectations with respect to the following factors have an important impact on the course of the MACC too:

- Future fuel price.
- Development of fleet structure.
- Learning effects w.r.t. abatement measures.
- Expected life time of measures.
- Level of autonomous efficiency improvement.

The level of the fuel price in the year under consideration has a strong impact on the level of the cost-effective abatement potential. Figure 6 illustrates clearly that the higher the fuel price, the higher the cost-effective abatement potential.

Figure 6 **Sensitivity of cost-efficient abatement potential w.r.t. future fuel price**



Source: CE et al., 2009.

The expected development of the fleet is crucial for the baseline emissions.

Learning effects can have an impact on the future costs as well as on the future reduction potential of an abatement measure. Assuming an increase of the reduction potential over time definitely has an impact on the maximum abatement potential and it can also have an impact on the cost efficient abatement potential. A decrease of the abatement costs over time leads to an improvement of the cost-effectiveness of the respective measure.

The expected life time also has an impact on the cost-effectiveness of a measure. The longer a measure is expected to live, the better its cost-effectiveness.

And finally the expected level of an autonomous efficiency improvement has an impact on both, the abatement potential presented in the MACC and on the assessment of the costs for achieving a certain emission level.

2.3 Comparative analysis

In the previous section, the elements that determine the run of a MACC have been discussed. A comparison of the three studies with respect to these elements shows that the studies differ mainly with respect to nine elements (see Table 2 for an overview).

CE et al. (2009) and IMAREST (2010a) allocate the individual CO_2 abatement measures to measure groups. The measures that are unlikely to be applied together or that exclude each other are thereby allocated to the same measure group. Setting up the MACC, one measure per group is then chosen that is the most likely to be applied to this segment. Eide et al. (2011) take into account that two measures exclude each other, i.e. fuel cells (used as auxiliary engines) and gas fuelled engines.

Table 2 **Main differences between the three studies**

	Eide et al. (2011)	IMAREST (2010a)	CE et al. (2009)
Modelling interaction btw. measures	All measures can be combined with each other except for fuel cells (used as auxiliary engines) and gas fuelled engines.	Grouping Combination reduces reduction potential in absolute terms	Grouping Combination reduces reduction potential in absolute terms
Baseline emissions	Autonomous efficiency improvement: 2010: 5% 2020: 8% 2030: 10%	Frozen technology baseline	Frozen technology baseline
Baseline emissions in 2030	~1,500 Mt	~2,000 Mt	Reduction potential in rel. terms only (~1,900 Mt)
Coverage of measure types	25 measures	22 measures, 15 groups	28 measures, 12 groups
Cost and reduction potential data in base year	2nd GHG Study data revised and amended	2nd GHG Study data revised	2nd GHG Study data
Fleet (age) structure	2008 fleet composition from LRF; SAI ship building and scrapping forecast for the short-run forecast; heuristic approach for long-term forecast	2007 age structure based on LRF data; 6 age categories of 5 yrs each; max. life time of ships = 30 yrs; IMO fleet data and forecast used for total ship numbers	Evenly distributed in 2007; max. life time of ships = 30 yrs; IMO fleet data and forecast used for total ship numbers
Fuel price 2030 (sensitivity analysis)	HFO: 350 USD/t MDO: 500 USD/t LNG: 350 USD/t	900 USD/t (700 USD/t, 1,100 USD/t)	700 USD/t (350 USD/t, 1,050 USD/t)
Discount rate (sensitivity analysis)	5% (8%)	10% (4%, 18%)	9% (4%, 14%)
Learning effects	Learning effects applied to several measures in terms of cost reductions and/or reduction potential increase; effect differs per measure.	For five innovative technologies, future cost reductions (10-15%) are anticipated for first 5 year period.	-

IMAREST (2010a) and CE et al. (2009) work with a frozen technology baseline. More precisely, the two studies work with the A1B scenario from the 2nd Greenhouse Gas Study and a sub scenario that is characterised by a medium demand level and the lowest level of transport efficiency improvement and speed reduction.[1] Baseline emissions in 2030 amount to 1,900 Mt in CE et al. (2009) and to about 2,000 Mt in IMAREST (2010a). In contrast, Eide et al. (2011) work with an autonomous efficiency improvement: “the improvement relative to the average ship in the current fleet is estimated to 5% for ships

[1] The lowest level is equal to zero in the 2020 forecast. In the 2050 forecast it is zero w.r.t. speed reduction and -0.05 with respect to transport efficiency. For 2030 total ship number have been interpolated.

built in 2010, increasing to 8 and 10% in 2020 and 2030, respectively." This autonomous efficiency improvement is not assigned to specific abatement measures.

IMAREST (2010a) and CE et al. (2009) take almost the same individual abatement measures into account: relative to the latter, IMAREST (2010a) has excluded five individual measures joined two, thus reducing the total number of measures included by five. Compared to CE et al. (2009) in IMAREST (2010a) the measures are allocated to 15 instead of 12 measure groups – it has been assessed that more measures can be combined. In Annex A, Section 0 a detailed overview is given on these measure groups and the allocation of the individual measures to these groups.

Eide et al. (2011) include a larger number of measures in the cost curve. The following 12 measures are taken into account in Eide et al. (2011) but not in the other two studies:

1. Fuel cells used as auxiliary engines.
2. Electronic engine control.
3. Frequency converters.
4. Gas fuelled engines.
5. Steam plant operation improvements.
6. Engine monitoring.
7. Contra-rotating propeller.
8. Wind power (fixed sails or wings).
9. Speed reduction due to improved of port efficiency.
10. Exhaust gas boilers on auxiliary engines.
11. Wind powered electric generator.
12. Cold ironing.

In contrast, the following 9 measures are covered in IMAREST (2010a) or CE et al. (2009) but not in Eide et al. (2011):

1. 20% speed reduction.
2. Wind engine (Flettner rotor).
3. Main engine tuning.
4. Common-rail technology.
5. Propeller-rudder upgrade.
6. Optimisation water flow hull openings.
7. Hull brushing.
8. Hull hydro-blasting.
9. Dry-dock full blast.

In Annex A, Section A.1 an overview of the coverage of the abatement measures is given for the three studies.

In all three studies, the cost and reduction potential data that underlies the MACC that is published in the 2nd IMO Greenhouse Gas Study is used. In IMAREST (2010a) and in Eide et al. (2011) the data has been reviewed by experts and changed slightly. In Eide et al. (2011) data for the extra measures covered has been added.

The fleet (age) structure is determined differently in the three studies. In CE et al. (2009) the annual total number of ships per ship segment is based on the IMO data and IMO forecast. The assumption is made that in the base year (2007) the ships are equally distributed w.r.t. their age per ship segment. Assuming that the maximum life time of ships is 30 years and knowing the total number of ships per year, the annual number of ships scrapped and added to the fleet can be derived. In IMAREST (2010a) the annual total number of ships per segment is also based on the IMO data and IMO forecast. However, the age structure of the fleet in the base year is based on the LRF Sea-Web ship database: six age categories of 5 yrs each are differentiated. Thus again the maximum life time of a ship is taken to be 30 years. Knowing the total number of ships per year, again the annual number of ships scrapped and new ships can then be derived. In Eide et al. (2011), the fleet composition for 2008 is taken from the LRF database. For the short-run forecast (3-5 yrs) of the fleet structure ship building and scrapping forecasts as published by the Institute of Shipping Analysis (SAI) are used. For the medium and long-term forecast a heuristic approach is used, assuming in the medium-run a downturn of orders as a consequence of the economic crises. In Table 3 annual scrap and growth rates used in Eide et al. (2011) are given for 5-year averages:

Table 3 **Annual scrap and growth rates used in Eide et al. (2011) (5-year average)**

	Scrap rates (%)	Growth rates (%)					
Year	All ship types	Oil	Dry bulk	Container	LNG	Others	Total fleet
2009	4	12	8	10	29	3	9
2010-2014	3	4	6	4	6	2	4
2015-2019	3	0	0	0	3	1	0
2020-2024	3	1	4	4	3	2	3
2025-2029	3	1	4	3	2	3	3

The three studies also differ as to the expected fuel oil price in 2030. In Eide et al. (2011) the fuel price is expected to be relatively low in 2030. The price for HFO and LNG it is assumed to be 350 USD/ton and for MDO 500 USD/ton. CE et al. (2009) expect an average fuel price of 700 USD/ton; a sensitivity analysis is carried out for ± 350 USD/ton. IMAREST (2010a) expect a relative high average fuel price: 900 USD/ton; a sensitivity analysis is carried out for ± 300 USD/ton.

As to the discount rate, different scenarios are presented in each of the three studies. In Eide et al. (2011) the main analysis is carried out for a discount rate of 5%. In sensitivity analysis results are also presented for a 8% rate. In IMAREST (2010a) and CE et al. (2009) main results are derived for higher, similar discount rates, i.e. 10 and 9% respectively; in a sensitivity analysis results are also derived for 4% in both studies and for 18 and 14% respectively.

The three studies finally also differ with respect to whether and inasmuch learning effects are taken into account. In CE et al. (2009) learning effects are not taken into account. In IMAREST (2010a) learning effects are expected for five innovative technologies: cost reductions of 10-15% are anticipated for the first 5 year period. In Eide et al. (2011) learning effects are applied to several measures in terms of cost reduction and/or increase of reduction potential. The learning effects differ per measure.

2.3.1 Can the differences in assumptions explain the differences in the MACCs?

In Table 1 the cost-effective and maximum relative abatement potential derived in Eide et al. (2011), IMAREST (2010a) and CE et al. (2009) are presented for the most comparable scenario. For these scenarios, the cost-effective relative abatement potential in 2030 is assessed to be slightly lower in IMAREST (2010a) and CE et al. (2009) compared to Eide et al. (2011) and the maximum relative abatement potential in 2030 is assessed to be significantly higher in Eide et al. (2011) than in IMAREST (2010a) and in CE et al. (2009).

When it is taken into account that, compared to CE et al. (2009), the expected average fuel price in 2030 is relatively high in IMAREST (2010a) and is slightly higher in Eide et al. (2011), the assessment the of cost-effective abatement potential can be expected to be the lowest in IMAREST (2010a), and can be expected to be similar in Eide et al. (2011) and CE et al. (2009), but the difference can still be expected to be rather small.

The different expectations with respect to the fuel price however have no impact on the assessment of the maximum relative abatement potential and can therefore not explain the significant difference between Eide et al. (2011) and the other two studies in this respect.

Taking into account that Eide et al. (2011) work with an emission baseline where autonomous efficiency improvement is taken into account, one would even expect that the maximum abatement potential is assessed to be lower. And, if the autonomous efficiency improvement is based on cost-efficient abatement measures, one would also expect the cost-effective abatement potential to be lower. This however is not the case.

A large share of the difference in the maximum abatement potential can be explained by the different abatement measures that are taken into account in the studies. Eide et al. (2011) take 12 abatement measures into account that are not considered in the other two studies. Visual inspection of the average MACC graph shows that these abatement measures account for about 400 Mt abatement potential. This extra abatement potential is also assessed to be relative high, since for most of these measures it is assumed that they can be combined. On the other hand, IMAREST (2010a) and CE et al. (2009) take 9 abatement measures into account that are not considered in Eide et al. (2011). However not all of these 9 measures can be considered as adding to the maximum abatement potential as derived in Eide et al.(2011), since most of these measures would only constitute a substitute for and not complement to measures accounted for in Eide et al. (2011). We estimate that these 9 measures account for 200 Mt extra abatement potential at most.

As to the overlapping abatement measures, which are considered in Eide et al. (2011) as well as in IMAREST (2010a) and CE et al. (2009), cost and reduction potential data for the base year does not seem to be an important source for this difference, since only slight changes have been conducted to the data that is underlying the MACC published in the 2nd IMO GHG Study. What seems to be much more relevant are the different levels of learning effects that have been assumed. In Eide et al. (2011) learning effects are applied in terms of an increase of reduction potential to several measures, e.g. to waste heat recovery, to exhaust gas boilers, energy efficient lighting and the air cavity system. An increase of the abatement potential of the measures over time has not been assumed in IMAREST (2010a) and in CE et al. (2009).

Figure 7 shows a quantitative comparison of the differences in the maximum abatement potential. Starting from the maximum abatement potential as reported in Eide et al. (2011), we have adjusted it for the baseline. Since CE et al. (2009) have a higher baseline, this results in an increase of the maximum abatement potential from 850 Mt CO_2 in 2030 to 1,040 Mt CO_2. If we subtract the twelve measures that are included in Eide et al. (2011) but not in CE et al. (2009), and add the measures that are included in CE et al. but not in Eide et al., the remaining potential is approximately 760 Mt CO_2. This is approximately 10% more than the maximum abatement potential as reported in CE et al. (2009). Hence, a major share of the difference can be attributed to two factors: a different baseline and a difference in measures. The remaining 10% difference can be attributed to differences in fleet composition and fleet rollover and learning effects of certain technologies.

Figure 7 Quantitative comparison of the differences in the maximum abatement potential

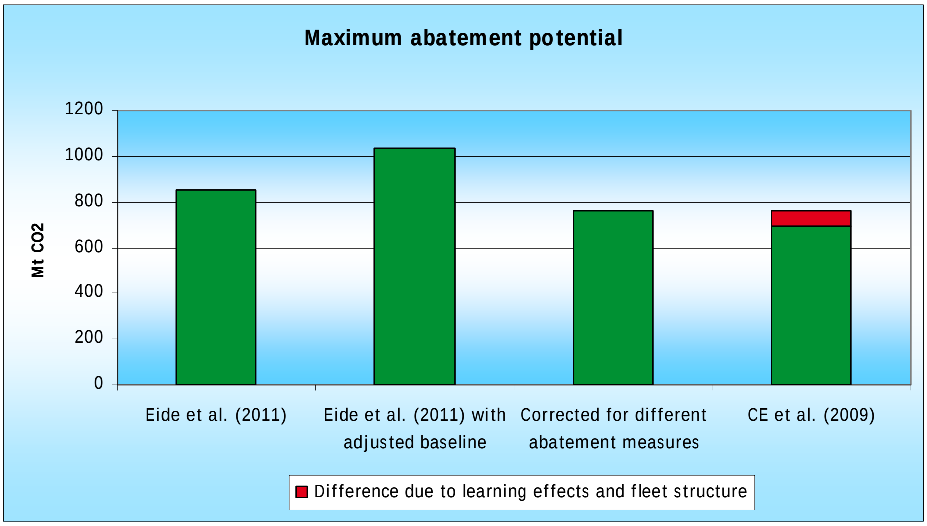
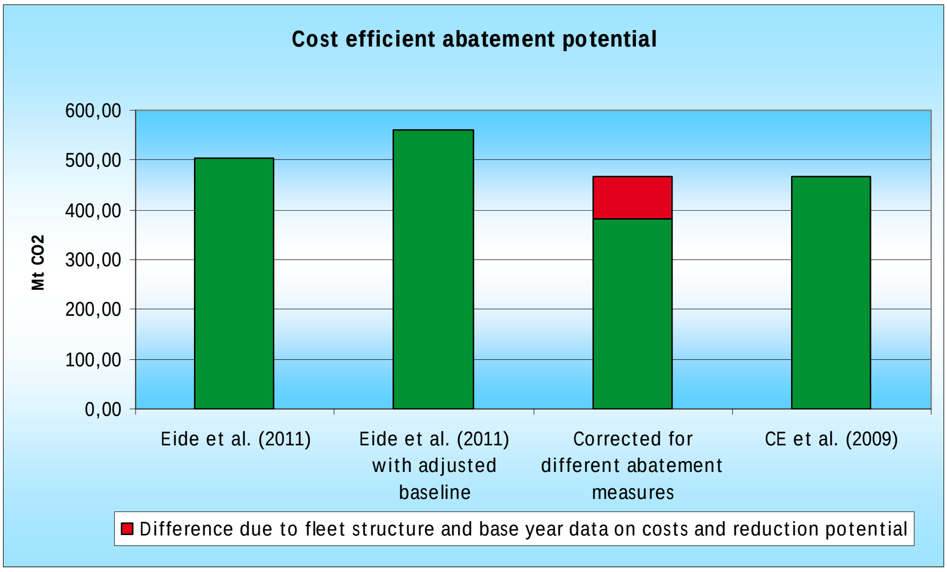


Figure 8 shows a quantitative comparison of the differences in the cost-effective abatement potential. Here, some assumptions have to be made that impact negatively on the quality of the comparison. We had to assume that measures which are cost-effective for a fleet average, are also cost-effective for each ship type and size category. While this is presumably not the case, this was the only way in which we could account for the difference in measures included in the two MACCs.

Starting from a cost-effective abatement potential of a little over 500 Mt CO_2 in the left bar of Figure 8, we again adjusted for the difference in the baseline, increasing the cost-effective potential to 560 Mt CO_2. The cost-effective potential of the measures that both MACCs have in common is shown to be about 380 Mt CO_2 in the third bar from the left. This is approximately 20% less than the cost-effective abatement potential as reported in CE et al. (2009) at the comparable fuel price of USD 350 per tonne of fuel. This difference can be attributed to the fact that some of the measures that are not cost-effective on average are cost-effective on some ship types in Eide et al., differences in fleet composition and fleet rollover and characteristics of certain technologies.

Figure 8 Quantitative comparison of the differences in the cost-effective abatement potential



2.4 Shape of the MACC

All MACCs for shipping have a similar shape: a rather shallow beginning with a negative cost-effectiveness, bending upwards and ending almost vertically (see Figure 1 through Figure 4). This section analyses the reasons for the shape, compares it with other MACCs and draws some general conclusions.

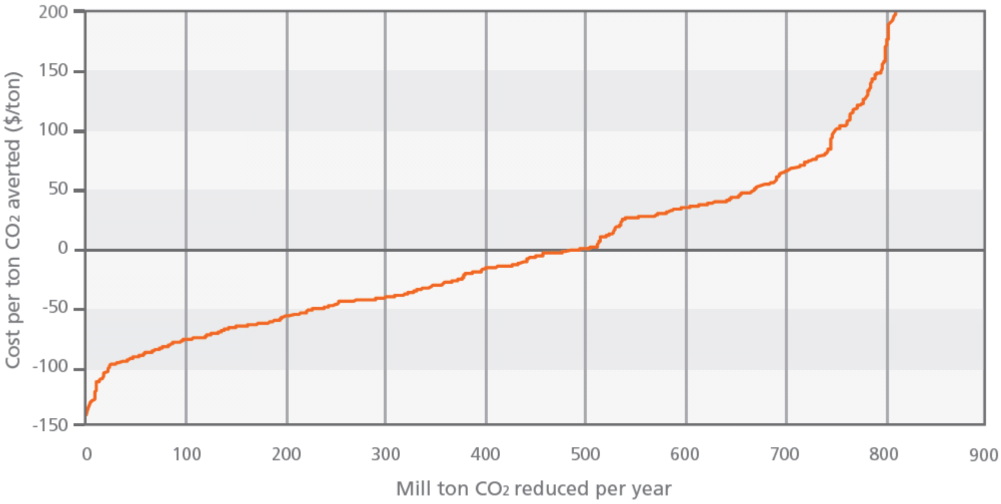
The shape of a MAC curve is to a large extent determined by two factors:
1. The measures included in the curve. And
2. The way in which the curve is represented.

We will discuss both factors subsequently.

The measures included in the curve are an important determining factor of the shape of a MACC. This is especially true for the almost vertical end of the curve. As can be inferred from the DNV curve (Figure 2), which excludes the least cost-effective measures, the end of the curve is dominated by measures like wind generators and solar cells, which have very high costs and a small abatement potential. Excluding these measures yields a significantly flatter curve.

There are several ways in which a curve can be presented. One is to include data on each measure applied to different ship types of different sizes. This yields a curve like in CE et al. (2009) (Figure 4) and IMAREST (2010a) (Figure 3). Another way is to aggregate the data by measure, in other words to present the fleet average cost-effectiveness of specific measures. This yields a curve like Figure 1 and Figure 2. By comparing these two sets, it becomes clear that the latter method yields a much shallower curve. This is also demonstrated by comparing Figure 2 with Figure 9, taken from the same publication, but using a different method to represent the data.

Figure 9 Detailed Abatement Curves For World Shipping Fleet 2030



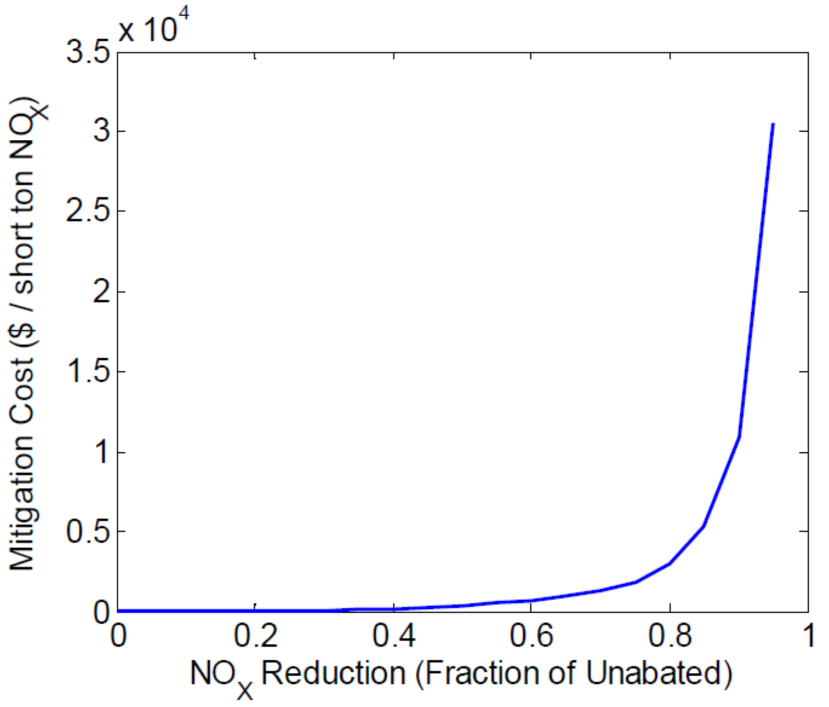
Source: DNV, 2010.

The reason why an aggregated presentation yields a shallower curve is that there can be a significant difference in the cost effectiveness of a specific measure when applied to different ships. For example, calculations underlying IMAREST (2010a) show that the cost-effectiveness of a 10% speed reduction varies from USD -210 per tonne of CO_2 to USD 1,500 per tonne of CO_2, depending on the ship type and size category. The weighted average cost-effectiveness of this measure is USD -60 per tonne of CO_2. Thus, by aggregating measures across ship types and size categories, the curve becomes shallower.

In summary, the steep end of a curve can be reduced by excluding just a few costly measures and the curve can be made to appear less steep by aggregating data.

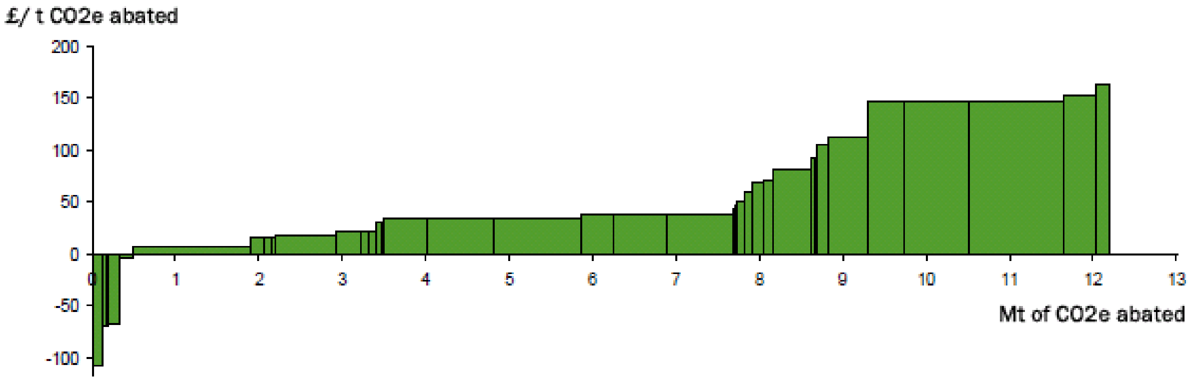
The shape of the shipping MACC is not unique. Figure 10 and Figure 11 show MAC curves for unrelated sectors, NO_x emissions from coal-fired utility boilers and CO_2 emissions from waste processing.

Figure 10 NO_x **Abatement Cost Curves for Coal-Fired Utility Boilers**



Source: IIASA, 2006.

Figure 11 **Marginal Abatement Cost Curves for the Waste Sector**



Source: Eunomia, 2008.

In many cases, the most costly options are new technologies or technologies that are attractive to niche markets only. This means that technologies which dominate the steep end of the curve are technologies that could be attractive to develop further, e.g. by R&D or innovation support, rather than by market based instruments. The cost-effectiveness of these options can be improved and their potential increased by pushing the technological frontier further (Kesicki, 2010).

2.5 Conclusion

This chapter has comparatively analysed three marginal abatement cost curves. The three curves are all based on the MACC as presented in the 2nd IMO GHG Study, but have been changed afterwards. The methodology is very similar. One study calculates the net present value of the measures if they are implemented in the year for which the MACC is calculated, the other two use annuitised costs. This does not result in significant differences, however.

The MACCs have different assumptions on fuel price and discount rates. These affect the cost-effectiveness of measures and the cost-effective abatement potential, but not the maximum abatement potential. They also have different fleet rollover assumptions.

The MACCs have a different methodology on how measures interact. While two MACCs exclude conflicting measures taken on the same ship (e.g. propeller boss cap fins, nozzles and propeller winglets), the other allows these measures to be taken on the same ship. This could potentially result in an overestimation of the maximum potential.

The MACCs have different business as usual baselines. Two MACCs have a frozen technology baseline with no autonomous efficiency improvements, while the other allows for efficiency improvements over time, which are not attributed to any of the measures in the MACC.

The main differences between the curves is their maximum abatement potential. One MACC has a considerable larger maximum potential than the other two. This can be attributed to a large extent to a difference in the baseline and a larger number of measures that are included. The remaining difference is about 10% and can be attributed to the other methodological differences.

3 Implementation of cost-effective measures

3.1 Introduction

Several studies have shown that many cost-effective abatement measures are not being implemented in the shipping sector (OECD, 2009; CE et al. 2009; IMAREST, 2010a; Eide et al., 2011). This is not unique to the shipping sector; there is a large body of literature on what is often called the energy efficiency gap (Jaffe and Stavins, 1994; Jaffe et al., 2001). Its existence may have several causes. First, there may be market *barriers*, such as low priority for energy issues and high demanded risk premiums; second there may be market *failures* (OECD/IEA, 2007), such as split incentives and transaction costs. Third, cost-effective measures may be an artifact of the way cost-effectiveness is calculated, e.g. real costs components may be overlooked or underestimated (see e.g. CE, 2009). Too high oil prices may have been assumed, for example, or the internal discount rate in the MACC does not reflect the market rates for investors.

Chicago school neoclassical economists would assume that the existence of cost effective measures, which are not implemented, *always* indicates calculation artifacts, i.e. that the costs of market barriers and failures ought to be included in the calculation of cost effectiveness (see e.g. Nickell, 1978). In their view the market barriers and market failures do not exist as they define optimality in terms of revealed preferences. In this view firms are profit maximising agents and if they decide not to invest in energy saving technologies, they do so because the benefits do not outweigh the costs. This view is debated, however: behavioural economics regards firms as satisficers rather than profit maximisers. Thus, they can cope with energy inefficiencies as long as they meet their expected profit margins. Others argue that the particular division of property rights will influence the outcomes. If not firms, but governments would be responsible for investment schemes, interest rates would drop as governments can lend money at more favourable conditions on the capital markets. Negative costs for energy saving measures then still reflect a suboptimal outcome, implying that social welfare could be enhanced if these measures were taken into account. The divergence between the social optimal outcome and the private outcome are called market failures (or market barriers).

This chapter adopts a practical approach to the energy efficiency gap in shipping. It analyses the literature on barriers to the implementation of cost-effective measures in Section 3.2, and reports on a series of interviews conducted with stakeholders on general and technology-specific barriers in Section 3.3.

3.2 Literature review

Several studies have looked into the reasons why not all cost-effective efficiency improvements are being implemented (CE, 2009; IMAREST, 2010a, Devanney 2010). CE et al. (2009) have identified a number of reasons, the four most important being:

1. The **low priority** given to improvements of fuel efficiency in the past. Over the past decades, shipping companies have focused on reducing crew costs rather than on reducing fuel costs. As a result, many shipping companies and other stakeholders lacked the knowledge to evaluate efficiency improving measures until recently. This was not irrational per se, as fuel was relatively cheap, so improvements in labour intensity yielded higher benefits than improvements in fuel efficiency. As fuel prices and fuel price forecasts have risen since around 2005, shipping companies and yards have paid more attention to fuel efficiency improvements.
2. The **split incentive** that occurs in much of the industry where fuel is paid by the charterer but technical modifications to a ship are paid for by the owner. Thus the owner is not always in a position to earn back his investments in fuel saving technologies. Even in market segments where the owner and the operator are the same, shipping companies are often shielded from fuel price increases, e.g. through the application of bunker adjustment factors.
3. Tthe **transaction costs** involved in gathering reliable information on fuel saving technologies may be high, and even more so for technologies that are not applied on a large scale.
4. There may be a **time lag** between a measure becoming cost-effective and its implementation due to the fact that a measure may be only implemented when a ship is in drydock.

Eide et al. (2010) only mention the split incentive as a barrier to the implementation of cost-effective measures, although they also hint at a more general 'lack of responsiveness to economics' in the shipping sector.

In addition to these reasons, Devanney (2010) provides anecdotal evidence of yards' resistance to change and owners resistance to change. In other words, the low priority given to fuel efficiency improvements extends to yards and may be linked to a general conservatism within the industry.

IMAREST (2010a) have classified the various barriers in three groups, adding financial barrier that stem from company specific investment appraisal methods:

1. Technological barriers
   a. Real or perceived risk of failure of a technology.
   b. Incompatibility of certain technologies with the ship and/or the routes where it sails.

2. Institutional barriers
   a. Split incentive in which the ship owner has to make an investment in a new technology while the charterer receives the benefit of lower fuel consumption.
   b. The split incentive combined with the fact that neither the charter market nor the second hand market pay a premium for fuel efficient ships.
   c. Bunker adjustment factors and other financial arrangements which shield the ship operator from the costs of fuel and thus make investments in energy saving less profitable.

d Lack of information on new technologies and/or the costs associated with finding out about new technologies.

3. Financial
   a Investment appraisal methods in shipping companies which require very short payback times for retrofit technologies.
   b Investment appraisal methods that prescribe a low fuel price in order to account for fuel price uncertainty.

3.3 Results from interviews

To understand the barriers regarding implementation of energy-efficient technologies, ship owners and other maritime stakeholders were interviewed regarding specific technological and operational measures.
Five different shipping companies were interviewed. Interview partners were the R&D managers and in one case the director of projects and new-building. The shipping companies have some different fleets:
1. Container ships and bulk carriers.
2. Container, Chemical, VLOC and PCTC ships and bulk carriers.
3. Cruise ships.
4. Heavy Lift and Multi-Purpose ships.
5. Bulk carriers, Multi-Purpose vessels and RoRo carriers.

Additionally, seven other maritime stakeholders were interviewed covering:
1. A shipyard, mainly for cruise liners.
2. A classification society.
3. An institute for maritime engineering.
4. An international shipping federation.
5. A maritime research institute.
6. An independent international shipping association.
7. A manufacturer of an innovative technology.

The shipping companies were asked which energy efficient measures are already applied and which are planned for the future. Further, they were enquired to give information regarding the expected energy saving potential and the costs of certain technologies, but these answered by none.
The other maritime stakeholders were invited to share their knowledge about the current status, i.e. if the different measures are already applied and their judgement about the future potential.
Section 3.3.1 reports on the section of the interview regarding general barriers. Technology specific barriers are discussed in Section 3.3.1.

3.3.1 General barriers

We have asked twelve stakeholders whether there are barriers and which barriers there are that prevent the implementation of energy saving measures on ships. This section presents an aggregated summary of these interviews. The reader should be aware that the conclusions drawn from the interviews reflect the assessment of the majority of the stakeholders and not of every stakeholder.

All the interviewees agreed that barriers exist that prevent the implementation of energy saving measures on ships. Some of barriers affect the market as a whole whereas others do affect small market participants only. Most of the interviewees recognised the barriers stemming from the literature review summarised in Section 3.2.

Six major barriers to the implementation of energy saving measures can be distinguished.

Low priority. First of all, many interviewees have indicated that, in general, energy efficiency of ships has not been ranked high on the agenda. A number of reasons are given for this, like low bunker fuel costs, a low environmental awareness and, until a few years ago, charter rates that allowed for a profitable operation of almost any ship. However, some interviewees perceive that the market currently is changing and that the awareness with respect to energy-efficiency is increasing.

Split incentives. In markets where ship owners do not operate their own ships, split incentives constitute a barrier to the implementation of energy saving measures too: the ship owner is the one to invest in the measure and the charterer is the one to profit from the investment. The charterer is often not allowed to make changes to the ships or has a short time horizon and is therefore not interested in making improvements in technical efficiency. Moreover, charterers, especially those chartering ships for a relatively short period of time, sometimes lack the technical expertise to rate the energy efficiency of the ships. Many interviewees have expressed the impression that charterers care little about the fuel efficiency of a ship. Exceptions exist, especially in long term charter markets where ship owners and charterers enter into a long term relationship. Some shipping companies have indicated that they require owners to inform them about the energy efficiency of a ship before they take it on lease.

For ship owners, guaranteeing a certain efficiency can be risky, since they do not always know in advance how a ship is operated. This makes them reluctant to guarantee a specific efficiency improvement. To arrange the sharing of costs and benefits between owners and charterers if there is a degree of uncertainty is a solution that can be observed in the market but is not common yet.

The interviewees disagreed about whether the EEDI and other indicators of fuel efficiency would increase the transparency in the market and allow owners of efficient ships to command higher charter rates. Some interviewees thought that the metric would allow for gaming and that it would take a long time for the market to get used to the metric. Others thought is could add transparency if it proved to be a reliable metric.

Lack of independent data. The third major barrier to the implementation of energy saving measures is the lack of trusted data on measures from an independent, third party. This barrier has been mentioned by shipping companies, research institutes and professional societies alike. This is especially of importance since the market is characterised by risk aversion with only some first movers that could provide such information. And first movers are not always willing to share their information. Small ship owners have no scope for carrying out their own tests.

Yards. The fourth major barrier is related to ship building. Ship yards offer standard designs and especially smaller owners may have problems with requiring changes to these designs. Some interviewees have the impression that yards have minimised the building cost of a ship, rather than the total costs of ownership. In a period of undersupply of ships changes are also not likely to be called for. Ship yards may be reluctant to make changes because of the warranties they give. Some ship owners indicated that established long term relationships with yards was a way around this problem.

Access to finance. The fifth major issue is, at least for small ship owners, the funding of the investment in energy saving measures. Whereas big ship owners are able to provide for internal funding or have relative easy access to credits, external funding may pose a problem for smaller ship owners. Some smaller shipping companies are able to overcome this problem by developing a ship in close cooperation with a charterer, thus providing additional security to a bank.

Route dependency of efficiency. The fact that the effectiveness of an energy saving measure is route-depended constitutes the sixth major barrier.
A measure can be highly effective on the one route, whereas it may be ineffective on the other. A measure that seems to be cost-effective for a specific ship type, may therefore turn out to be actually cost-ineffective. In the worst case, a ship may no longer be able to take certain routes when it adopts a certain measure. This could for example be the case when overall dimensions are adjusted.

3.3.2 Barriers for specific technologies

The technology-specific part of the questionnaire was sub-divided into following sections:

1. Technical measures.
    a Reduction of resistance.
    b Engine related measures.
    c Other technical measures.
2. Alternative fuels and power sources.
3. Operational measures.

Outcome

10 out of 12 interview partners answered the questions regarding specific technological and operational measures to improve the efficiency of the fleet. One shipping company did not want to answer the questions, but claimed that they apply nearly all of the proposed technologies and operational measures. However, the data are not included in the analysis, but would change the figures slightly. The results of the interviews are discussed in the next chapter followed by a separate analysis of the four ship owners alone.

Results

Technical measures

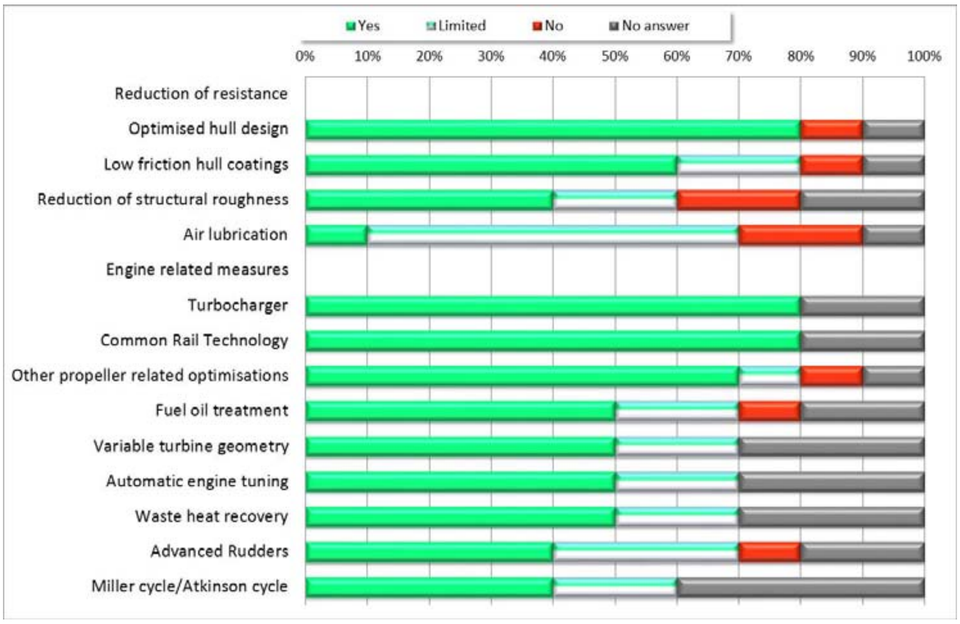
Reduction of resistance (Figure 12)
There is a strong perception that the **optimisation of the hull design** is important to improve energy efficiency. For certain ships the hull design is optimised continuously e.g. in towing tanks, whereas some say that it is difficult sometimes to get shipyards to accept a new ship design. The latter seems to be the highest barrier for a change in ship design.

The awareness and expectations for **low friction hull coatings** also seem to be very high, however, the savings potential is difficult to prove. One ship owner prefers to keep the conventional self-polishing antifouling to prevent biofouling of the ship hull. Some regard the alternatives as too expensive. Therefore the lack of proven savings potential and high costs pose barriers.

The **reduction of structural roughness** has less importance, as there is less awareness and understanding by the ship owners regarding the impact of macro-roughness on ships speed, but some research is going on.

There is a very high barrier for the application of **air lubrication**. The interest was very low by all ship owners that have been interviewed, due the complexity, unsuitability for certain ship types and failure during high wave action. There is also huge uncertainty regarding the efficiency. Finally, the power consumption to produce compressed air has to be taken into account. However, air lubrication is observed by the other maritime stakeholders.

Figure 12 Technical measures: Reduction of resistance and engine related measures already applied



Engine related Measures (Figure 13)

Most of the engine related measures especially **turbo charger, common rail technology and automatic engine tuning or electronic engine control** were regarded as state of the art by the ship owners. There was only one exception where the shipping company only applies turbo chargers and common rail technology and none of the other measures. Also variable turbine geometry, Miller and Atkinson cycle are regarded as proven technologies to improve fuel efficiency, but are also implemented for the reduction of NO_x emissions. Knowledge about the special engine related measures was very low outside the ship owners community. Therefore many other stakeholders did not answer the questions. For the directly engine related optimisations there seem to be little barriers.

Other propeller related optimisations are regarded to have medium impact. Ship owners apply flow improvement fins (boss fin caps) and propeller polishing. A lot of research is going on in this area. There are surprisingly little barriers, although the costs can be high and there is a risk of high maintenance.

The main barrier for the implementation of **waste heat recovery** and **advanced rudders** was found to be the costs as they are considered to be extremely expensive. “Waste heat recovery is fancy to have but very expensive”, was one of the statements. The vast majority of ships do not have enough power or heat to power the waste heat technologies. Therefore, it is not applicable or suitable for all ship types. Some ship owners see a high potential especially for cruise liners, others use the waste heat for fuel oil heating only.

Fuel oil treatment is regarded to have only limited impact on energy efficiency. The saving potential could be 2%. Some additives work by increasing lubrication some do not. The biggest barrier (authors knowledge) is engine manufacturers warrantees, as the fuel and lube oil specifications are quite strict. In case of an engine failure the warranty might expire. New innovative technologies like electrolytic treatment of fuel oil to decrease viscosity seem to be unknown in the maritime market. Therefore, the biggest barriers are confidence and lack of knowledge.

The **propeller** is regarded as most important and improvements pose an advantage, but **advanced rudders** are very expensive and there is also a risk of introducing new failures. The propeller and the shaft are regarded as highly sensitive and highly stressed parts. Therefore changes in these areas are investigated carefully. A lot of research is going on in the area of advanced rudders, especially for fast ships. The main barrier is the costs, risk of failure and high maintenance.

Other technical measures

The **optimisation of hotelling functions** is well perceived by the maritime industry especially for passenger ships. The energy saving potential for these ship types is huge. The cruise liners use power optimisation programs for ventilation, light, etc. There is a lower effect on all other ship types, but still this energy saving option is implemented by shipyards and designers. It will also be part of the SEEMP.

Electric propulsion is applied by cruise liners only, as it is very dependent on the operational profile of the ships. For long fixed routes this does not seem to be a solution nowadays. However, electric propulsion is a good measure to optimise and control energy consumption. This can improve efficiency, but at higher costs. The expected saving potential is 6-8%.

Minimising the weight of the ship and the use of **lightweight materials** represents a huge saving potential for passenger ships, but not so much for other ship types. Weight can only be reduced to a certain extent. In most ships freight constitutes 70-80% of the water displacement. So only limited total weight reductions can be achieved. Moreover, the lifetime of a ship and its strength pose limits. In terms of light weight material one big barrier is the lack of suitable materials and safety aspects. For example high tense steel causes cracking.

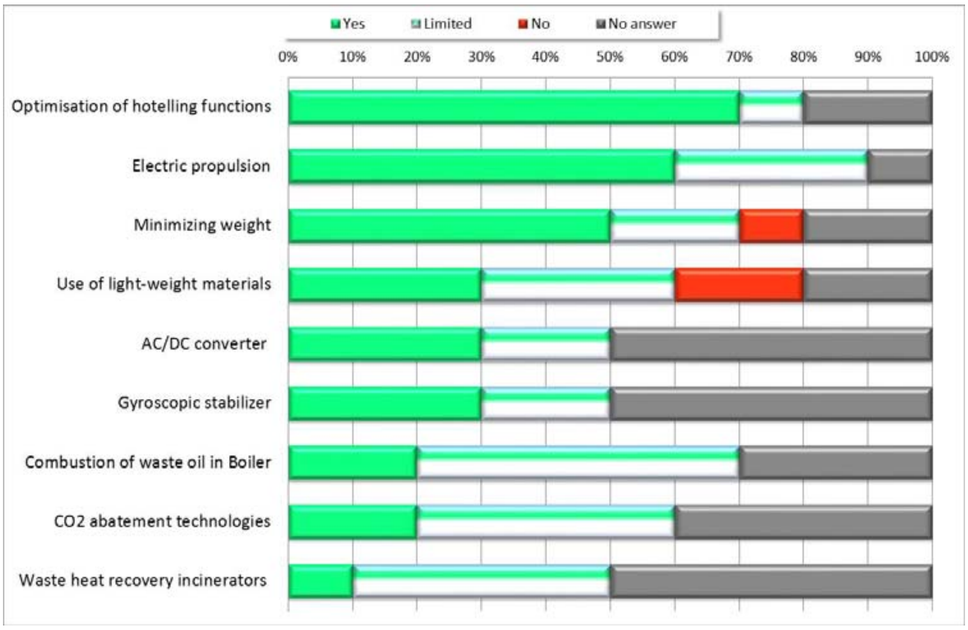
AC/DC converters are increasingly used in special ships such as passenger ships, special purpose vessels. They are useful on ships with a high base load like cruise liners. Thyristor controlled rectifiers are used to convert AC to DC power for high power requirements like azipods and electric propulsion, as the energy consumption can be optimised. Savings are also good in terms of space and energy loss through the cables and instruments. However, AC/DC converters are not suitable for all ship types. As a result of the interviews it was found that the general knowledge about AC and DC power is quite low and consequently is regarded as the highest barrier. Only one ship owner applies the thyristor technology.

Combustion of waste oil is not well perceived due to costs ("about 10 times more expensive to burn sludge than land it"), and environmental concerns, as the exhaust gas will contain many pollutants. Further, local regulations limit the combustion of waste oil in certain areas. Only one ship owner has the

technical option installed on several ships. The barriers are therefore costs, environmental concerns and legislation.
CO_2 abatement technologies do not increase the fuel efficiency, but reduce GHG emissions of ships. These are in a research and pilot stage at two ship owners, others tend to observe. The main barrier here is the trust in the technology and the conservative behaviour of the maritime scene.

Waste heat recovery of incinerators is not well known as not all ships have waste incinerators. Incinerators waste heat recovery is only used on passenger ships like cruise liners. The barriers therefore are lack waste incinerators, lack of knowledge, but also technical problems which might outbalance the benefit.

Figure 13 Other technical measures already applied



Alternative fuels and power sources

Cold ironing (shore power) does not save energy, but reduces local emissions. Only one ship owner has installed shore power connections on several ships. There are a number of barriers. The most important is the deficiency in standardisation of power supply (variable frequency, voltage and connectors). The second is that ship owners want to have power from renewable energy sources, but this is not guaranteed by the energy suppliers. Others regard cold ironing as counterproductive, as a highly effective power plant is already on board.

LNG and CNG also do not save energy, but are very interesting as alternative fuel in terms of price and emission limits for NO_x and SO_2. Yet the costs for ship construction increase significantly, although this does not pose a barrier. Barriers are the low availability of LNG and CNG, lack of infrastructure for supply and the size of storage tanks (lack of space). Nowadays these fuels are only attractive for gas carriers and for short sea shipping like ferries. Most of the ship owners are watching the developments carefully.

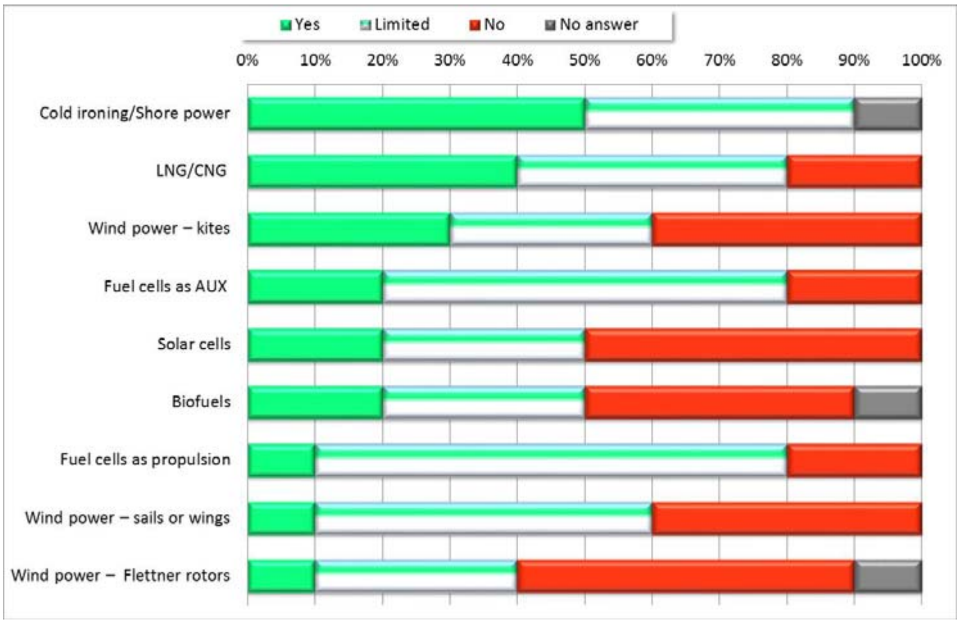
From the three **wind power** options, the use of kites has the lowest acceptance due to operational limitations, kite durability and replacement costs and difficult handling. One ship owner is in a trial stage. All three technologies are dependent on wind directions and therefore on the operational profile of the ship. Additionally the **kites, wings and sails** are only suitable for relatively slow ships (10–15 knots) and the flettner rotors could cause some stability problems. The interview partners however know that all of the options are in a trial stage and one ship owner is investigating the impact on ship design. In summary there is interest, but many limitations.

Fuel cells are regarded a promising technology but not mature enough at the moment. There are a number of research projects going regarding their implementation on ships. The application as auxiliary power is more than 5 years away and as main propulsion more than 30 years. None of the interviewed ship owners apply fuel cells on their ships today, but it is known that fuels cells are used for submarines and for small ferries. The barriers are lack of maturity, but also cost. Fuel cells and hydrogen are very expensive compared to other fuels.

Solar cells are only suitable for a niche market like cruise liners, car carriers and ferries (ships with a large available top surfaces). Yet the power generation per square meter is very low.

Biofuels do not save energy and do not seem to be an attractive measure in shipping. There is limited supply of biofuels, no cost advantage and the production is regarded to have very negative environmental impacts. The interviewed cruise liner company stopped the use of biofuels due to costs and bad public reputation.

Figure 14 Alternative fuels and power supplies already applied



Operational measures

General speed reduction is believed to have the highest impact on energy efficiency. However, this issue is still very market driven and depends on charter contracts (charter rate/day) and fuel prices. Further, the ship has a specified design speed and needs to maintain its flexibility in terms of weather, cargo, etc. Otherwise, speed reduction is regarded as a very strong tool, probably the most promising.

Weather routing is applied by all ship owners and is well accepted. The saving potential depends on ship routes. Savings can be made especially on North Atlantic and Pacific routes. The indirect saving is the prediction of arrival time and therefore the possibility to run the ship at a constant lower speed instead of driving at full load. There are no barriers at all.

Trim optimisation is well accepted in the maritime industry, nearly state of the art. One ship owner started to improve training to raise awareness on the benefits of correct trim in relation to fuel savings. On large containerships savings up to 10% can be achieved. Further improvement would be the combination with ballast water optimisation. There is software available on the market to improve trim and ballast water. There does not seem to be any barrier, instead a medium to high potential for power optimisation.

Voyage optimisation is well known and is applied by most shipping companies. The saving potential is regarded as medium up to high. The barriers are the contracts with charter parties and port mentality.

A lot of effort is put into **the increase of awareness and regular training of the crew.** Awareness is increased by sending monthly environmental bulletins to the crew, increase of competition and comparison of ships regarding fuel efficiency, accidents and emissions. One stakeholder also reported about a propulsion based payment or salary applied in cruise liner industry. Others say that awareness in combination with training decides the most about energy efficiency in shipping. Classification societies support this with a software tool. Some ship owners have environmental officers, which provide on board training for the crew. The saving potential is regarded as very high (up to 20%). There are no barriers at all.

Autopilots optimise the steering of a ship under different weather and load conditions. All interviewed ship owners make use of autopilots in their fleet. One ship owner states that the autopilot is part of their SEEMP. The saving potential is very high and there is room for improvements. There is no barrier at all.

Monitoring of energy consumption is applied by two ship owners. The other two can only record fuel consumption by the amount of fuel bunkered after a voyage, but this is not the same. The monitoring of fuel consumption is regarded to have a high potential, especially for crew awareness training. No barrier was identified, but the authors view is that active energy monitoring instrumentation is very expensive.

Optimised fleet management is applied by three of the ship owners, but there is still space for improvement. The limited information given to this option does not allow identifying any barriers.

Regular hull and propeller cleaning reduces the drag caused by biofouling and is regarded to have a huge saving potential. However, the conventional self-polishing antifouling coatings are not suitable for polishing, as the paint would be polished causing a peak release of biocides into the environment. Only two interviewed shipping companies have implemented the regular propeller and hull cleaning. The other problem is the local release of invasive species, which can cause the same problems like ballast water. This can be subject to local legislation like in Australia and New Zealand. Here the limited application is due to the type of coatings and possibly due to legislation.

Speed reduction due to port efficiency is sometimes applied by two ship owners and is routinely applied in container shipping, but is generally also dependant on the charter contracts. It is believed that there is a high saving opportunity, but it requires a shift in port mentality (e.g. queues in ports). There is also a potential for short sea shipping on fixed routes.

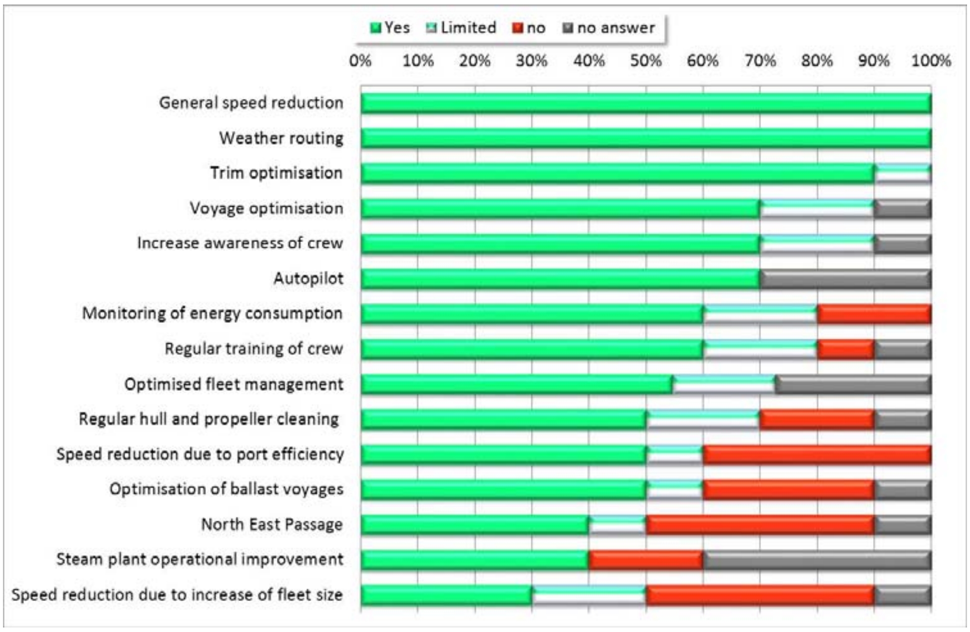
Optimisation of ballast voyages is not applied on cruise liners, as they do not have as much ballast water as other ships and should always carry passengers. Another ship owner currently investigates this option. Otherwise optimisation of ballast voyages is applied and it is well known that ballast water and ballast voyages should be kept at a minimum. The only barrier could be commercial aspects.

North East Passage is a special case of voyage optimisation, but is limited to some months in summer due to ice coverage. Ships sailing the Northern Route require the highest ice class, are guided by ice breakers and require approval from the Russian Authorities. Consequently there are a number of barriers: weather conditions, ships' ice class, costs for ice breakers and time for the Russian approval.

Steam plant operational improvement is regarded as state of the art, but limited to ships that have boilers. Steam plants use the waste heat from the flue gas. Only two of the ship owners apply steam plant optimisation, however some believe that there is a good potential to save energy. The barrier is the principal use of steam plants. Steam as propulsion became very rare.

Speed reduction due to an increase of the fleet size is not applied by any of the interviewed ship owners. The other stakeholders could report that this applied to a limited extent. There a general agreement that this measure offers a huge opportunity to save energy and to increase the effective use of the fleet. The main barrier is that the fuel is still too cheap compared to the cost of a new ship, which is reflected by a careful cost-benefit calculation. There is also the opportunity to increase the size of single ships to reduce the costs per ton of cargo, which more common practise.

Figure 15 Operational measures already applied



Analysis of ship owners questionnaires (Figure 16)

Four out of five ship owners answered the detailed questions. One shipping company only reported that most of the technological and operational measures are applied in their fleet. However, this information is not reflected by the graphs as no detailed information was given

The most important energy reducing measures are the operational optimisations (Figure 15), which should be reflected in the MACCs to a large extent. The largest impact on MACCs is expected by the general speed reduction and by increasing the environmental awareness of the crew, followed by the frequent training of the crew. All interviewed shipping companies use weather routing, trim and voyage optimisation and make use of autopilots. However the savings potential is unknown. So far no ship owner increased its fleet size to reduce speed.

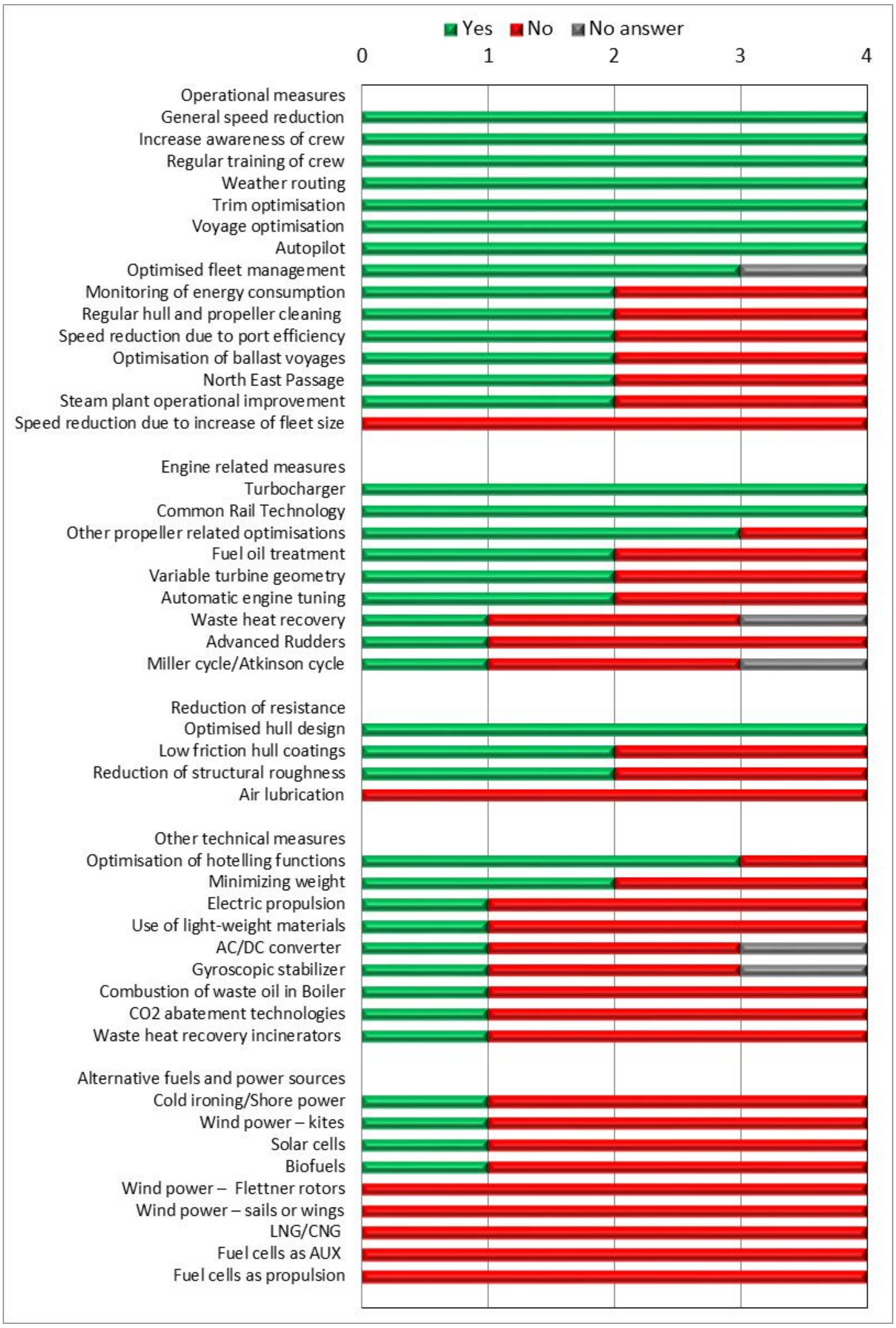
The second important energy measure improvements are engine and propeller related. Most of the engine related measures are state of the art and are implemented. This should be echoed by the MACCs. Most ship owners also try to improve the water flow around the propeller rather than investing in expensive advanced rudders. The reason might be costs and safety aspects.

Reduction of resistance is important as all ship owners optimised their hull design to reduce resistance, whereas reduction of friction by coatings and structural roughness was applied by two ship owners only. The reason is the uncertainty in savings potential and cost-benefit. Air lubrication was not applied at all due to technical constraints and complexity. The latter technology should appear in the MACCs in the higher end.

Other important energy saving measures are optimisation of hotelling functions and minimising weight. All other measures in this section have less importance or sometimes are unknown and are applied in cruise liners only.
CO_2 abatement technologies are in a trial stage at one ship owner and are currently planned by another shipping company.

The least promising measures are in the section alternative fuels and power sources. There is huge interest in LNG/CNG as future alternative fuel, but there is a lack of infrastructure and ship construction becomes more expensive. Wind propulsion is applied by one ship owner on a trial basis but the general view is that this is not suitable for most ships. Fuel cells are not ready for the maritime market, especially not as main propulsion. Solar cells deliver too little energy at high costs. Biofuels were applied by one ship owner in the past, but not anymore due to its bad reputation. The figures surely will change and have an impact on MACCs when fuel prices increase.

Figure 16 Analysis of already applied technologies and measures by the different shipping companies



3.4 Conclusion

There are a number of general barriers to the implementation of cost-effective abatement measures. These are:

- At least until a few years ago, ship owners and operators paid little attention to the fuel efficiency of their ships.
- In many cases, there is a split incentive since the ship owner has to invest in fuel saving technologies while the charterer reaps the benefits. Due to

the variability of actual fuel use, it is risky for the ship owner to guarantee a low fuel use and hence the fuel efficiency is not reflected in the charter market.
- In general, there is a lack of independent data on fuel saving technologies.
- Yards often consider fuel saving technologies a risk and may not be willing to offer them.
- Due to risks associated with new technologies, it may be hard to finance them externally.

In addition, there are technology specific barriers.

The barriers for the application of the different energy efficiency measures are largely suitability for the different ship types, costs, uncertainty regarding the saving potential, technical problems and infrastructure for alternative power supplies. The motivation to implement new technologies will be increasing fuel costs. As the MACCs are very dependent on the development of fuel prices, this will change the shape of the curve significantly.

The overall comparison of the different measures showed that the optimisation of operational measures is most important. The reason might be a comparable little effort for the implementation, little technological changes of the ship structure and comparable low investment. Ship owners and other maritime stakeholders both judged these measures as the highest energy saving measure and therefore have a huge impact on the MACCs. In detail the most accepted operational measures are speed reduction, increase of crew awareness and crew training. Awareness is e.g. increased by fuel saving competition between crews and ships.

Engine related measures are well perceived by the ship owners, whereas the knowledge other maritime stakeholders was very low. Most engine related improvements are regarded as state of the art and are also related to reduction of NO_x emissions. They should appear in the MACCs as already applied technologies. Improvements in engine performance are largely dependent on new developments at the engine manufacturers. Barriers for the other technologies are the high costs for e.g. waste heat recovery and advanced rudders. Changes to the propulsion system are not only costly but also regarded as very sensitive in term of ships safety. Therefore there is a strong reluctance for the implementation and should appear in the tail of the MACCS. Fuel oil treatment has the lowest potential and is regarded as very uncertain with little potential and is not implemented on a broad basis.

Reduction of ship hull friction is well accepted as energy saving measure, especially the optimisation of the ship hull design. Optimisation of the ship hull design is state of the art. The only barrier is the acceptance at the shipyards, who do not like changes of designs. The extent of the fuel saving potential is mainly unknown. The barriers for low friction hull coatings are uncertainty of saving potential and high costs. Air lubrication was the least accepted method for a number of technical and operational reasons. Energy savings between 1-10% are possible, but air lubrication is simply not suitable for most ship types and has very limited potential to be implemented.
Other technical measures are less accepted or simply unknown. On the top range are optimisation of hotelling functions and minimisation of weight. The remaining technological measures are mainly applied on cruise liners only and not relevant for other ship types. Here the MACCs should differ significantly for the different types of ships with high impact on cruise liners and less impact for other ship types.

The lowest acceptance was for alternative fuels and alternative power sources. Ship owners largely do not accept alternative power sources and other maritime stakeholders see a limited or no impact at all. Shore power is applied by one ship owner and largely fails due to standardisation of the power supply.

Fuel cells are not regarded as mature for shipping and are only applied in a very small niche market. It will take many years until fuel cells can be implemented in ships, especially as main propulsion. Even when the technical problems are solved, the price of the technology and hydrogen has to be much lower to support the implementation of fuel cells. Wind power is applied by one ship owner only in a ship trial. Kites have the lowest acceptance compared to flettner rotors, sails and wings. Barriers are the handling, costs for the replacement parts plus the fact that they are only useful on relatively slow ships (<15 knots). However, if wind propulsion is applied, there will be a huge impact on the MAC curve, as the saving potential can be very large. The barriers for the use of LNG and CNG are lack of infrastructure for their global supply, increase of shipbuilding costs and space requirements. All ship owners are very interested in the use of LNG/CNG, but observe the developments only. This alternative fuel again can only be applied in a niche market like gas carriers and short sea shipping.

4 Conclusion

4.1 Comparison of the MACCs

This report has analysed and compared three marginal abatement cost curves. The three curves are all based on the data as presented in the 2nd IMO GHG Study, but have revised some of the data and included additional measures. The methodology that has been applied to calculate MACCs is very similar.

The MACCs have different assumptions on fuel price and discount rates. These affect the cost-effectiveness of measures and the cost-effective abatement potential, but not the maximum abatement potential. They also have different fleet rollover assumptions.

The MACCs have a different methodology on how measures interact. While two MACCs exclude conflicting measures taken on the same ship (e.g. propeller boss cap fins, nozzles and propeller winglets), the other allows these measures to be taken on the same ship. This could potentially result in an overestimation of the maximum potential.

The MACCs have different business as usual baselines. Two MACCs have a frozen technology baseline with no autonomous efficiency improvements, while the other allows for efficiency improvements over time, which are not attributed to any of the measures in the MACC.

The main differences between the curves is their maximum abatement potential. One MACC has a considerable larger maximum potential than the other two. This can be attributed to a large extent to a difference in the baseline and a larger number of measures that are included. The remaining difference is about 10% and can be attributed to the other methodological differences.

4.2 Barriers to the implementation of cost-effective measures

The published MACCs do not account for barriers to the implementation of certain measures but rather show the potential emission reductions that could be achieved if all the measures would be implemented. The barriers were studied in a separate part of this study.

There are a number of general barriers to the implementation of cost-effective abatement measures. These are:

- At least until a few years ago, ship owners and operators paid little attention to the fuel efficiency of their ships.
- In many cases, there is a split incentive since the ship owner has to invest in fuel saving technologies while the charterer reaps the benefits. Due to the variability of actual fuel use, it is risky for the ship owner to guarantee a low fuel use and hence the fuel efficiency is not reflected in the charter market.
- In general, there is a lack of independent data on fuel saving technologies;
- Yards often consider fuel saving technologies a risk and may not be willing to offer them.
- Due to risks associated with new technologies, it may be hard to finance them externally.

In addition, there are technology specific barriers. Some measures identified in the MACCs are considered to be risky, unreliable, or otherwise unwanted by ship owners and operators. In some cases, this may be due to lack of independent data; in others, the assumptions on costs and abatement potential used in the MACC curves may be too optimistic.

The results from the analysis of the barriers has implications for the MACC and give rise to policy recommendations.

4.3 Impact of barriers on MACC

The purpose of a MACC is to show the abatement potential and the associated costs of various emissions target. It can be argued that MACCs should not take barriers into account. However, if barriers are clearly linked to specific technologies, one could merge them with the MACCs.

For several technologies, there appear to be significant technological barriers to the implementation of measures. Some measures are not considered to be effective, e.g. low friction hull coatings and air lubrication. Since both have a considerable potential in the published MACCs, incorporation of this barrier in the MACC would adjust the abatement potential downwards. Other measures are considered to be risky or very costly, e.g. kites and waste heat recovery systems. For some measures, ship owners indicated that fairly long drydocking periods were needed to implement them. Incorporating these barriers in the MACC would shift the curve upwards and reduce the cost-effective abatement potential.

For some technologies, there are no barriers as they are widely applied by the stakeholders contacted. This is the case for speed reduction, weather routing, trim optimisation, turbochargers and a set of other measures. To the extent that these measures have become state of the art, they should be excluded from the MACC. This would reduce both the maximum and the cost-effective abatement potential.

The MACCs studied here do not include optimised design of new build ships. The reason is probably that the costs and the abatement potential are very hard to quantify. However, many stakeholders we have interviewed indicated that substantial savings can be made in this area.

4.4 Policy recommendations

It is clear from both the literature review and the interviews that important barriers exist to the implementation of cost-effective technologies. Two important barriers appear to be the lack of independent information and the split incentive between owners and charterers. Both could potentially be addressed by policy measures.

Independent information can be provided by government-supported research institutes, centers of excellence, and so on. Furthermore, information can be gathered by encouraging pilot projects for the implementation of measures, coupled with dissemination of the experiences gained. In a broader context, independent information could be provided as technology transfer to and capacity building in developing countries.

The split incentive can to a degree be remedied by providing the market with good metrics to evaluate the fuel-efficiency of ships. The EEDI could be one of those metrics, although according to many stakeholders, it still has to prove itself in practice. If it turns out to be a reliable metric, regulators could consider extending the EEDI to existing ships in order to increase the transparency in the market.

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Annex A Abatement measures

A.1 Coverage of studies with regard to the individual abatement measures

The following table gives an overview of the different CO_2 abatement measures that underly the MACCs in the different studies. Note thereby that summing up the ticked boxes per column does not give the actual number of measures considered in the studies. This is the case because both a measure group with which is worked in a study is given (e.g. reduced auxiliary power usage) but also single measures which could be subsumed to this group (e.g. speed control of pumps and fans) with which in the other study is worked are given.

Table 4 **CO_2 abatement measures underlying the MACCs of the different studies**

	Eide et al. (2011)	IMAREST et al. (2010a)	CE et al. (2009)
Main engine tuning	-	x	x
Common-rail	-	x	x
Electronic engine control	x	-	-
Frequency converters	x	-	-
Gas fuelled engines	x	-	-
Steam plant operation improvements	x	-	-
Waste heat recovery	x	x	x
Engine monitoring	x	-	-
Propeller-rudder upgrade	-	x	x
Propeller upgrade (nozzle, tip winglet)	x	x	x
Propeller boss cap fins	x	x	x
Improvement flow to/from propeller	x	x	x
Contra-rotating propeller	x	-	-
Propeller performance monitoring	-	-	x
Propeller polishing	x	x	x
Air lubrication	x	x	x
Hull coating	x	x	x
Hull performance monitoring	-	-	x
Hull brushing	-	x	x
Hull hydro-blasting	-	x	x
Dry-dock full blast (old ships)	-	-	x
Optimisation water flow hull openings	-	x	x
Towing kite	x	x	x
Wind power (fixed sails or wings)	x	-	-
Wind engine (Flettner rotor)	-	x	x
Speed reduction due to improvement of port efficiency	x	-	-
Speed reduction 10% (due to fleet increase)	x	x	x
Speed reduction 20% (due to fleet increase)	-	x	x
Reduced auxiliary power usage (low energy lighting etc.)	x	x	x
Speed control of pumps and fans	x	x	x
Energy efficient light system	x	x	x
Exhaust gas boilers on auxiliary engines	x	-	-
Solar panels	x	x	X

	Eide et al. (2011)	IMAREST et al. (2010a)	CE et al. (2009)
Fuel cells used as auxiliary engines	x	-	-
Wind-powered electric generator	x	-	-
Power management system	-	-	x
Cold ironing	x	-	-
Optimisation trim/draft (based on load condition)	x	x	x
Voyage optimisation using shaft power meter	x	-	x
Voyage optimisation using fuel consumption meter	x	-	x
Voyage execution (const. speed and load; rudder position)	x	-	-
Weather routing	x	x	x
Autopilot upgrade/adjustment	-	x	x

A.2 Measure groups IMAREST (2010a) and CE et al. (2009)

In IMAREST (2010a) and in CE et al. (2009) the individual CO_2 abatement measures are grouped. The measures that are not likely to be used together/that exclude each other are thereby allocated to one group. As can be seen in the following overview, in IMAREST (2010a) five individual measures are taken less into account and two measures were joined, whereas three more measure groups are differentiated. In Table 5 those measure groups that differ are listed first.

Table 5 Comparison of measure groups in IMAREST (2010a) and CE et al. (2009)

IMAREST (2010a)		CE et al. (2009)	
Measure Group	**Individual Measure**	**Measure Group**	**Individual Measure**
Weather routing	Weather routing	**Voyage and operations options**	Weather routing
Autopilot upgrade/adjustment	Autopilot upgrade/adjustment		Autopilot upgrade/adjustment
	-		Optimisation using shaft power meter
	-		Optimisation using fuel consumption meter
Reducing onboard power demand (hotel services)	Low energy lighting	**Auxiliary systems**	Low energy lighting
Speed control of pumps and fans	Speed control of pumps and fans		Speed control of pumps and fans
	-		Power management
Propeller maintenance	Propeller polishing (at regular intervals)	**Propeller maintenance**	Propeller brushing (at regular intervals)
	Propeller polishing (when needed; including propeller performance monitoring)		Propeller brushing (increased frequency)
			Propeller performance monitoring

IMAREST (2010a)		CE et al. (2009)	
Hull coating	Hull coating I	**Hull coating and maintenance**	Hull coating I
	Hull coating II		Hull coating II
	-		Dry dock full blast
	-		Hull performance monitoring
Hull cleaning	Hull brushing		Hull brushing
	Underwater blast		Underwater blast
Speed reduction	10% speed reduction	**Speed reduction**	10% speed reduction
	20% speed reduction		20% speed reduction
Optimisation hull openings	Optimisation water flow of hull openings	**Retrofit hull improvement**	Transverse thruster opening (flow optimisation, grids)
Air lubrication	Air cavity system	**Air lubrication**	Air cavity system
Propulsion upgrade	Propeller-rudder upgrade	**Propeller/propulsion upgrade**	Propeller-rudder upgrade
	Propeller upgrade (nozzle, tip winglets, etc.)		Propeller upgrade (nozzle, tip winglets, etc.)
	Propeller boss cap fins		Propeller boss cap fins
Main engine adjustments	Common rail technology	**Main engine retrofit measures**	Common rail technology
	Main engine tuning		Main engine tuning
Waste heat recovery	Waste heat recovery	**Waste heat recovery**	Waste heat recovery
Wind power	Towing kite	**Wind power**	Towing kite
	Wind engines		Wind engines
Solar power	Solar power	**Solar power**	Solar power

Annex B Questionnaire

Questionnaire for maritime stakeholders

This questionnaire helps to identify the efforts of the maritime industry to reduce GHG emissions. The results will feed into a GHG study and will help to identify the differences in the various published marginal CO2 abatement cost curves. The study is carried out by CE Delft and Marena Ltd for the Ocean Policy Research Foundation, Japan. Names of companies and individuals will be treated confidential and are only classified into major groups, unless agreed otherwise. We thank all parties for their contribution.

1. Barriers to the implementation of energy saving measures

Several studies have indicated that shipping companies can increase the energy efficiency of their ships at no costs or even at a profit. DNV, for example, has estimated that on average, ships can improve their energy efficiency by 10% while at the same time reducing their costs. What is your opinion about these studies?

1.1 Several studies have looked into the reasons why not all cost-effective efficiency improvements are being implemented. IMarEST (2010) has identified a number of reasons:

1. Technological barriers
   a. real or perceived risk of failure of a technology
   b. incompatibility of certain technologies with the ship and/or the routes where it sails

2. Institutional barriers
   a. split incentive in which the ship owner has to make an investment in a new technology while the charterer receives the benefit of lower fuel consumption
   b. the split incentive combined with the fact that neither the charter market nor the second hand market pay a premium for fuel efficient ships
   c. bunker adjustment factors and other financial arrangements which shield the ship operator from the costs of fuel and thus make investments in energy saving less profitable
   d. lack of information on new technologies and/or the costs associated with finding out about new technologies

3. Financial
   a. investment appraisal methods in shipping companies which require very short payback times for retrofit technologies
   b. investment appraisal methods that prescribe a low fuel price in order to account for fuel price uncertainty

Questions

1.1.1. Do you think these barriers exist?

1.1.2 Do you think other barriers are also important? If so, which?

1.1.3. Which barrier or barriers are the most important in your opinion?

1.2 Many stakeholders have perceived the split incentive to be an important reason why not all cost-effective technologies are implemented. This means that a charterer will not pay a premium for a more fuel efficient ship, even though he has to pay less for the fuel.

1.2.1 Is this true, in your opinion, and if so, why isn't the fuel-efficiency reflected in the charter rate?

1

1.2.2 If you charter a ship, do you assess its fuel efficiency and if so, how?

1.2.3 Will the increased transparency in the market (e.g. EEDI and EEOI) change this situation?

1.2.4 Are some technologies perhaps regarded as risky so that they actually result in lower charter rates? If so, which?

1.2.5 How do you think that innovative technologies affect the second hand price of a ship?

1.2.6 Do the classification societies approve all technologies?

1.2.7 Do you have a specific fuel price in mind when assessing different technologies?

1.2.8 **In general,** do you think the general mentality is to watch others before taking action?

1.2.1 do shipowners wait for the legislation to be in place before applying an energy saving measure?

2

2. Energy Efficiency Measures: State of the Art/Plans for the Future

Which energy efficiency measures do you believe is already applied and accepted by shipowners and which are most promising from your point of view? Under comments the measures can be related to certain ship types.

2.1 Technical measures

No.		Already applied	Application planned	(Expected) Energy saving (%)	Costs	Comments
1	**Reduction of resistance**					
2	Low friction hull coatings to reduce roughness of wetted surface					
3	Reduction of structural roughness (e.g. less hull openings					
4	Optimised hull design to reduce wave resistance					
5	Air lubrication					
6	Electric propulsion					
	Engine related measures					
7	Turbocharger					
8	Common Rail Technology					
9	Variable turbine geometry					
10	Miller cycle/Atkinson cycle					
11	Automatic engine tuning					
12	Waste heat recovery					
13	Fuel oil treatment e.g.					
14	Advanced Rudders					
15	Other propeller related optimisations					
	Other technical measures					
16	AC/DC converter For the propeller and generator					
17	Optimisation of hotelling functions					

3

No.		Already applied	Application planned	(Expected) Energy saving (%)	Costs	Comments
18	Minimizing weight					
19	Use of light-weight materials in ship construction					
20	Waste heat recovery incinerators					
21	CO_2 abatement technologies					
22	Gyroscopic stabiliser					
23	Combustion of waste oil in Boiler					
24	Others					

2.2 Alternative fuels and power sources

No		Already applied	Future potential	(Expected) Energy saving (%)	Costs	Comments
1	Cold ironing/Shore power					
2	Fuel cells as AUX (hybrid auxiliary power generation)					
	Fuel cells as propulsion					
3	LNG/CNG					
4	Biofuels					
6	Wind power – kites					
7	Wind power – sails or wings					
8	Wind power – wind generators (Flettner rotor)					
9	Solar cells					
10	Others					

4

2.3 Operational measures

No		Already applied	Future potential	(Expected) Energy saving (%)	Costs	Comments
1	General speed reduction					
2	Speed reduction due to port efficiency					
3	Speed reduction due to increase of fleet size					
4	Weather routing					
5	Voyage optimisation					
6	Steam plant operational improvement					
7	North East Passage					
8	Trim optimisation					
9	Optimisation of ballast voyages					
10	Monitoring of energy consumption					
11	Autopilot					
12	Regular hull and propeller cleaning					
13	Increase awareness of crew					
14	Regular training of crew					
15	Optimised fleet management					
16	Others					

5