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GHG emission reduction potential of EU-related maritime transport and on its impacts

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Abstract

A study of the GHG emission reduction potential of maritime transport up to 2030 was executed under a contract of the European Commission (contract no. CLIMA.B.3/ETU/2013/0015).

In this study a reference scenario and CO_2 abatement scenarios were developed for global and EU-related maritime transport from 2012 to 2030. The reference scenario included the analysis of: the transportation volume, the economic growth rate (4.25% global and 1.55% for Europe annually) and the development of ship specifications (growth of average ship size and implementation of EEDI and LNG as a fuel). The abatement scenarios were based on Marginal CO_2 Abatement Costs Curves for ten individual vessel categories.

According to the reference scenario, the annual CO_2 emissions of the EU-related maritime transport would increase from 190 million ton in 2012 to about 208 million ton in 2030. The abatement scenarios would lead to CO_2 emission reductions in the range of 15% to 30% in 2030 , compared to the reference scenario for 2030, and 7% to 18% reduction compared to the 2012 reference. In most cases these reductions are with savings in Total Costs of Ownership (TCO – sum of investment & operational costs).

Executive Summary

A study of the potential GHG emission reduction of maritime transport up to 2030 was executed under a contract of the European Commission (contract no. CLIMA.B.3/ETU/2013/0015). The study is carried out by a consortium of ISL, MARINTEK, TML and TNO. The main objective of the study is the development of Marginal CO_2 Abatement Costs Curves for about ten vessel categories and to develop several scenarios for the application of abatement measures and its impacts on the CO_2 emissions of maritime transport and its economic impacts.

Reference scenario
Based on the third and earlier IMO[1] studies, projections are made of the CO_2 emissions per vessel segment. Consequently a reference scenario was developed for the GHG emissions of global and European maritime transport between 2012 and 2030. The reference scenario included the Economy of Scale (gradual growth of average ship size), the implementation of the EEDI and the gradual application of LNG. With the reference scenario, the European maritime GHG emissions increase moderately from 190 million ton CO_2 annually in 2012 to about 208 million ton of CO_2 annually in 2030 (black line in Figure s3). If the same transport volume would be transported with the 2012 vessel characteristics, the annual CO_2 emission would be about 250 million ton.

CO_2 abatement scenarios and costs
For ten vessel categories (dry bulk, general cargo, container, reefer, RoRo & vehicle, oil tanker > 80' dwt, oil tankers 80'dwt, chemicals, LNG & LPG carriers and RoPax), the costs and benefits were evaluated for the following types of abatement measures:
- Technical measures
- Operational measures
- Alternative fuels and cold ironing

These technical and operational measures were modelled in Marginal Abatement Costs Curves (MACC) for each vessel category (see Figure s1, for container vessels). This example shows that over 20% fuel and CO_2 can be saved with measures that also save money. For the most costly measure, namely 'waste heat recovery', the CO_2 reduction costs are high, about EUR 300 per ton CO_2 reduction. Also for alternative fuels and cold ironing, the costs are high or show a broad range depending on energy prices:
- LNG: can save costs or can be expensive: up to around 900 EUR[2] per ton CO_2 reduction, depending on the LNG price.
- Biofuels: around 200 EUR per ton CO_2 reduction.
- Hydrogen auxiliary power: 600 – 800 EUR/ton CO_2.
- Cold ironing: cost neutral to up to about 375 EUR/ton CO_2, depending on electricity price.

In the next step, the following scenarios were modelled:
- No regret abatement: application of all abatement measures which (individually) save costs (and lower Total Costs of Ownership, TCO)
- Zero costs abatement: application of all abatement measures up to the point that the costs (TCO) are the same as for the reference

[1] The Third IMO GHG Study 2014. Reduction of GHG emissions from ships. Imo.org. The second IMO GHG Study 2009, The first IMO GHG Study 2000. Refer to Reference list in section 7.
[2] EURO is used as standard currency throughout this report. Where necessary an exchange rate of 1.20 USD per 1 EURO is used.

- Maximal abatement: application of all investigated abatement measures (Figure s1). This may lead to a higher TCO as for the reference.
- Maximal abatement + alternative fuels.

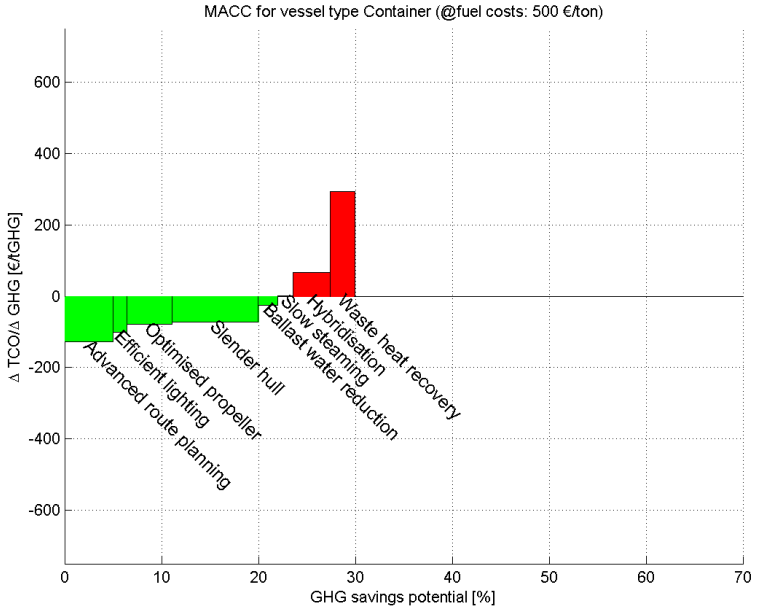

Figure s1: Marginal Abatement Costs Curve for container vessel (fuel price 500 EUR/ton).

The scenarios were processed for three fuel prices: 250, 500 and 1000 EUR/ton fuel. In that way the consequences are evaluated for a broad fuel price range[3].

This leads to the following conclusions regarding the potential GHG savings for new ships**:**

- Based on the middle fuel price of 500 EUR/ton, in a no-regret scenario, the total GHG savings potential is between 15% and 50%, depending on the vessel category.
  In a zero-cost scenario GHG savings ranges from about 25% to 60% depending on the vessel category. For a number of categories, the maximal abatement is achieved with a costs reduction. This is dependent on the fuel price.
- Based on the low price, 250 EUR/ton, the no regret savings ranges from 0% to 29% depending on vessel category.
- Based on the high price, 1000 EUR/ton, this range becomes 23% to 54% savings.
- In a maximum-reduction scenario, the total GHG savings potential is between 30% and 59%, depending on the vessel category. For 8 out of 10 categories, the maximal abatement is achieved at a net saving compared to the reference scenario.

For the future projection (2012-2030), it is assumed that both technical measures and operational measures will be applied to new ships, and that operation measures will be applied to existing ships. For the remaining vessel categories; ferry-pax; cruise; yacht; offshore; service; fishing and other (unspecified), it is assumed that the abatement potential is 50% of the average for the cargo vessels. This results in the global scenario results per vessel category presented in Figure s2.

[3] Recent history shows that fuel prices are very unpredictable.

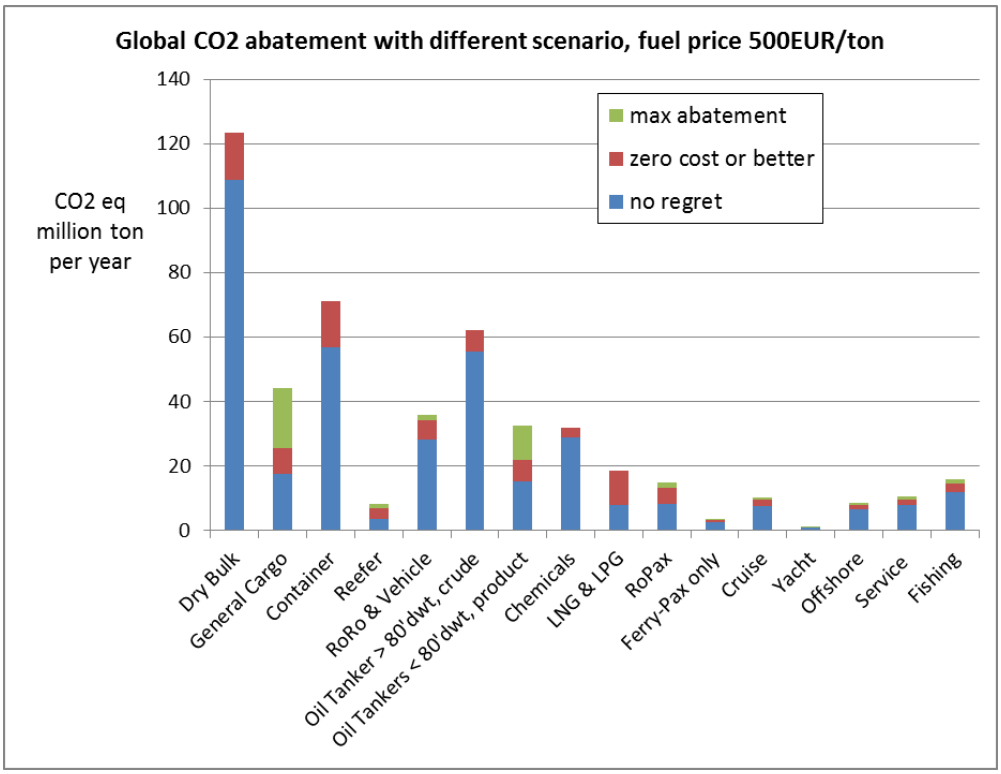

Figure s2: Potential GHG savings of global maritime transport per vessel type in 2030

For the European maritime transport, a projection is made based on an economic growth rate of 1.55% annually. This is lower than the global economic growth of 4.25% annually. The results are presented in Figure s3.

Consequently, the conclusions for the European GHG emissions of maritime transport (covering voyages from and to EU ports) for 2030 are:

- With no regret abatement measures, the 2030 European maritime CO_2 emissions can be lowered from 208 million ton (reference scenario) to between 156 and 177 million ton depending on the fuel price. This is 15% to 25% reduction compared to the reference scenario. The reduction is then 7% to 18% compared to the 2012 levels.
- With zero costs abatement measures, the CO_2 emissions can be reduced to 147 to 161 million ton depending on the fuel price. This is a 23% to 29% reduction compared to the reference scenario (and 15% to 23% compared to 2012).
- With maximal abatement, the CO_2 emissions can be reduced to about 146 million ton CO_2 eq. This corresponds to a reduction of 30% compared to the reference scenario.
- With additional use of alternative fuels (LNG, biofuels, H2 fuel cells and cold ironing), the CO_2 emissions can be further reduced to about 137 million ton of CO_2 eq, a further reduction of about 6%.
- Depending on the abatement scenario, the CO_2 emissions would continue to rice until around 2020. After that they would actually go down despite the yearly growth of transport volume.

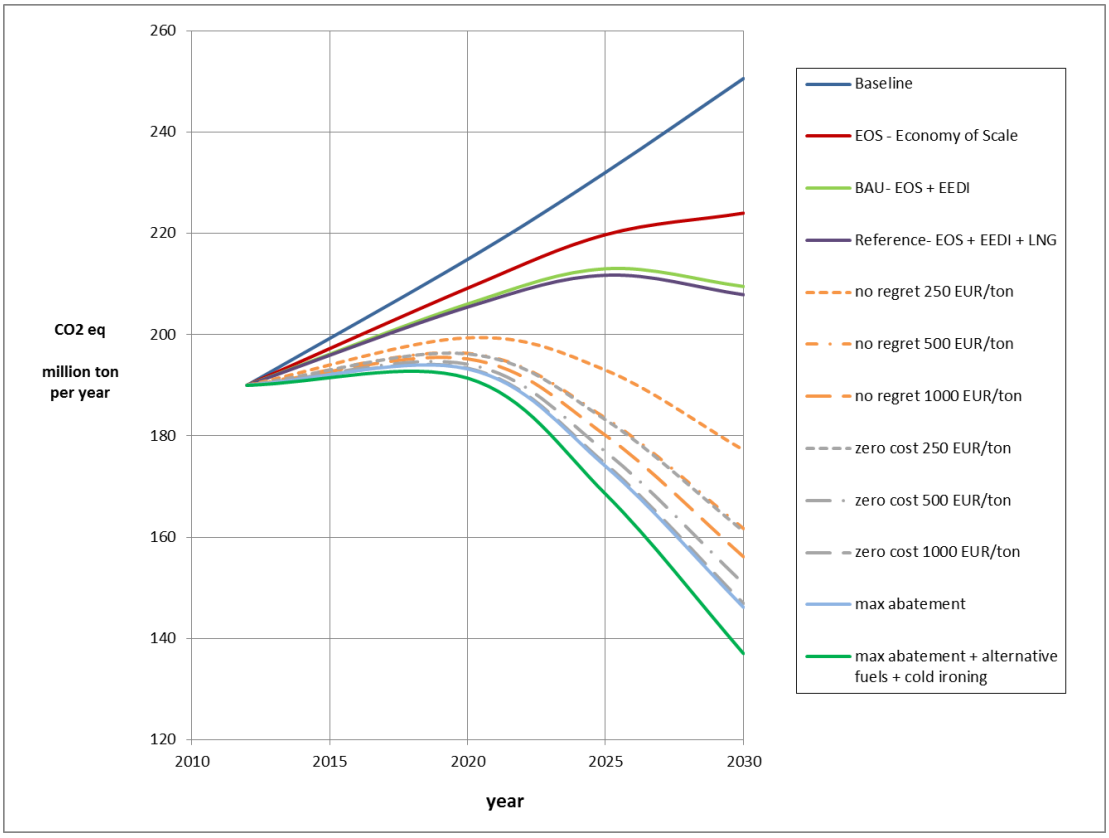

Figure s3: European maritime transport emissions for the assessed abatement scenarios, including additional use of alternative fuels (LNG, biofuels H2 fuel cells) and cold ironing.

Pass through of savings or costs

The pass through of savings or costs (from the application of abatement measures) to the customers of the shipping company was analysed. This was done with an economic model and the price elasticity's of substitution for each market segment of the vessel categories. . For this analysis, it is assumed that the abatement measures have been implemented on 25% of the shipping fleet.

The analysis has led to the following conclusions:

- Savings and costs due to CO_2 abatement measures are usually shared between shipping company and its customers.
- For almost all vessel types, both shipping companies and their customers benefit from the abatement measures under the scenario 'no regret' and 'zero cost', because it results in lower prices and an increased profit margin for the transportation company.
  Price reductions range from about 0.1% to almost 4%, while the average profit margin would increase by 0.1% point or less (nominal 5%).
- Under the 'maximal abatement' scenario, the prices would increase up to 26% (for general cargo, but mostly below 10%) and the profit margins are reduced by about 0.1% point or less.

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Appendices

A Fleet projection for different vessel segments
B Reference vessels
C Data for the maritime market model

1. Introduction

This project has been carried out by a consortium of ISL, MARINTEK, TML and TNO under the contract no. CLIMA.B.3/ETU/2013/0015 “GHG emission reduction potential of EU-related maritime transport and on its impacts”.

With this study, the European Commission would like to get a better insight of the greenhouse gas emission reduction potential for the near future (up to 2030) for EU-related ship voyages and for individual shipping segments. The Commission also would like to better understand the impact of the recent economic crisis, especially for Europe, on the expected development of greenhouse gas emission from maritime transport. The greenhouse gas emission reduction potential should be presented for different scenario such as ‘no regret’ abatement measures, meaning measures which clearly reduce shipping costs. Also ‘zero cost’ (combination of profitable measures and not profitable measures up to the point that the shipping costs are the same as the original situation) and maximal abatement scenarios are defined and subsequently analysed.

1.1 Objectives of the study

The main objective of the project was to identify the marginal GHG abatement costs in the maritime sector and the no-regret GHG reduction potential from maritime transport up until 2030.

More specifically the objectives were:

- To prepare abatement costs curves for a number of shipping segments, for EEA port related segments and for the overall EEA related maritime transport.
- To include both technical design improvements on new ships and operational efficiency measures on new and existing ships.
- To perform a sensitivity analysis on a range of relevant drivers, which include GDP growth and in its geographical distribution, fuel type and price variations.
- To analyse the pass through of costs and savings of GHG abatement measures

In our approach we combine qualitative methods, including literature review and stakeholder consultation, with quantitative methods using state of the art models and databases.

1.2 Structure of the report

Table 1 summarises the seven tasks and the main activities of each task.

Table 1: Description of main tasks of the project

Task	**Main activities or approach**
Task 1: Identify drivers	1. EU port related fleet projection for the different vessel segments, including new building activity and fuel consumption projection 2. Identification of drivers for CHG emissions (per segment) 3. Assessment of relative impact of drivers per segment
Task 2: Reference scenario	1. Translate" the drivers as identified in task 1 to model parameters 2. Quantify key drivers for future emissions and build the business-as-usual scenario for EU related CO_2 emission 3. Establish sensitivity scenarios
Task 3: Abatement potential	1. Define abatement options and their costs 2. Define three abatement scenarios (including sub-scenarios) 3. Calculation of impact of scenarios on CHG-emissions 4. Consultation of scenario's with stakeholders
Task 4: Pass through of costs	1. Identify the most relevant commodities (EXIOMOD model) 2. Identify the division of the passing through between different actors in the supply chain 3. The quantification of the pass-through of costs and savings to the final consumer for each scenario identified in Task 3
Task 5: Impact on third countries	The quantification of the pass-through of costs and savings to the final consumer in the non-EEA countries for each scenario identified in Task 3.
Task 6. Stakeholders consultation	Obtain feedback on the following items: - Drivers and the development over time (task 1) - Reference scenarios (task 2) - Abatement options (task 3) - Pass through of costs (task 4)
Task 7: Synthesis & delivery of the results	- presentation of main conclusions and recommendations, - preparation of final report
Task 0: Project Management	Project Management

The interrelationship of the WPs is shown in Figure 1.

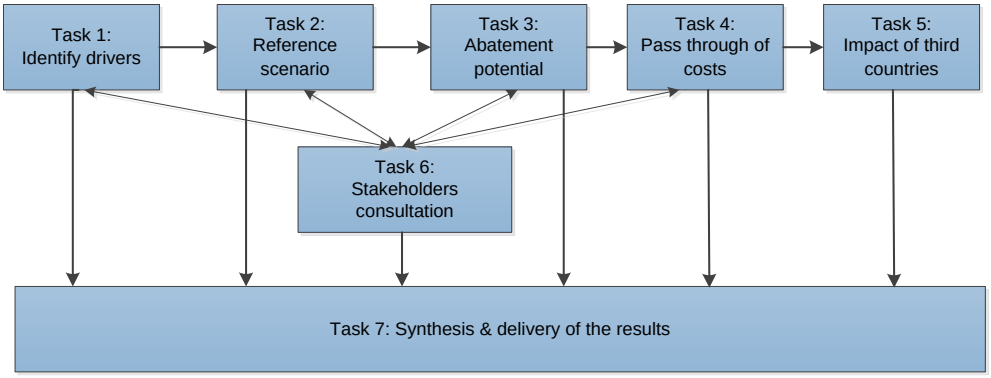


Figure 1: Work Package organisation

2. Identify drivers [task 1]

The environmental consequences of the increased trade have become important as a result of the current climate debate. Anthropogenic emissions of greenhouse gases (GHG) contribute to global warming, and augmentations in temperature to more than 2°C above pre-industrial levels are likely to have catastrophic consequences at a global level (Walker and King, 2008). These implications are well documented by the Intergovernmental Panel on Climate Change (IPCC) which was established in 1988 and acknowledged by our politicians. It is estimated that greenhouse gas emissions need to be reduced by around 50% – 85% in 2050, as compared with current levels, in order to achieve a stabilization of the temperature at 2°C above pre-industrial levels (IPCC, 2007).

2.1 Earlier studies

Carbon dioxide (CO_2) is the most important greenhouse gas emitted by ships while other greenhouse gas emissions from ships are less important (Buhaug et al., 2009). According to the Second IMO GHG Study 2009 (Buhaug et al., 2009) for the International Maritime Organisation (IMO), maritime transport emitted 1046 million tons of CO_2, in 2007, representing 3.3% of the world's global anthropogenic CO_2 emissions. These emissions are assumed to increase by 150% – 250% in 2050 if no action is taken, i.e. business as usual scenarios (BAU) with a tripling of world trade. This means that total emissions in 2050 are foreseen to be at 2.5 to 3.5 times today's level. Similar growth prospects have also been reported by OECD (2010) and Eyring et al. (2009). These greenhouse gas emission growth figures stand in sharp contrast to the required total global reductions (IPCC, 2007). Nevertheless, it is a controversial issue how the annual greenhouse gas reductions shall be taken across sectors. Given a scenario where all sectors accept the same percentage reductions, the total shipping emissions in 2050 may be no more than 15% – 50% of current levels based on the required 50% – 85% reduction target set by the IPCC (2007). Moreover, provided that the demand for sea transport follows the predicted tripling of world trade, it can easily be deduced that the amount of CO_2 emitted per ton nautical mile will then as a minimum, have to be reduced from 20 gram to 4 gram of CO_2 per ton nautical mile by 2050. This is a reduction by a factor of 5 to 6 and a seemingly substantial challenge. The question is thus how to realize the required greenhouse gas reductions, and at the same time meeting the mission objectives of sea-transport systems.

2.2 Policy and Legislation

On the international scene the current international discussion within the United Nations Framework Convention on Climate Change (UNFCCC) which was established in 1992 also covers international shipping. The Kyoto Protocol established in 1997 invites Annex I countries (article 2.2) to the protocol to pursue the limitation or reduction of greenhouse gas emissions from shipping through the International Maritime Organization (IMO). Headquartered in London and established in 1948 by the United Nations (UN), IMO promotes cooperation among governments and the shipping industry to improve maritime safety and to prevent marine pollution.

In the late 1980s, IMO started its work on prevention of air pollution from ships. The first regulatory steps were out-phasing of ozone depleting substances used in refrigerant systems and firefighting systems. In 1997 an air pollution annex, annex VI, was added to the International Convention for the Prevention of Pollution from Ships (MARPOL Convention), which sets amongst others strict rules for nitrogen oxides and sulphur oxides emissions in the exhaust gas. Developments in regulating maritime carbon emissions started in the same year (1997) when the MARPOL conference adopted a resolution requesting IMO to undertake a study on greenhouse gas emissions from ships and to consider feasible emission reduction strategies.

In 2000, the first IMO GHG Study (Skjølsvik et al., 2000) was published, which estimated that ships engaged in international trade in 1996 contributed about 1.8% of the world total anthropogenic CO_2 emissions. In 2003, the IMO Assembly adopted Resolution A.963 (23) related to the reduction of greenhouse gas emissions from ships which urged, IMO's Marine Environmental Protection Committee (MEPC), to identify and develop the mechanisms needed to achieve reduction of GHG emissions from international shipping. In October 2006 the 55th session of the Marine Environmental Protection Committee agreed that IMO should continue to take lead in developing GHG reduction strategies for international shipping. The Committee agreed to a work plan to develop technical, operational and market based methods for dealing with greenhouse gas emissions and to update the IMO 2000 GHG study. The work plan culminated at the 59th session of MEPC in July 2009 with the presentation of the Second IMO 2009 GHG study and the approval of the principles for a mandatory Energy Efficiency Design Index (EEDI) and a Ship Energy Efficiency Management Plan (SEEMP). Two years later in July 2011 at the 62nd session of MEPC, the EEDI and SEEMP were adopted as parts of the MARPOL Convention (Resolution MEPC.203 (62)). The EEDI uses a formula to evaluate the CO_2 emitted by a vessel per unit of transport as a function of vessel type and size. The formula has been established by grouping vessels built during the past 10 years into vessel types such as container and dry bulk, and then generating the average values and baselines as a function of size and type by a standard regression model. Common to all vessel types is that as vessel sizes increase, their emissions per transported ton cargo decreases. It should be noted that the EEDI is a technical standard where the measurement is based on the CO_2 emitted when the vessel is fully loaded, and with the speed which it achieves under calm water conditions, when the power outtake from the main engine(s) is 75% of maximum. This in contradiction to the Energy Efficiency Operational Indicator (EEOI), which measures the real operational performance of cargo-carrying vessels, but which so far, is for voluntarily usage.

And regarding the EEDI, only marginal reductions will be achieved unless the thresholds are becoming stricter and stricter for each decade in the future. Due to this the discussion in IMO continues regarding how much stricter the requirements per vessel shall be for new-built vessels. The core of this discussion is different views about availability of new technology and what are achievable emission reductions with more energy-efficient hull forms and designs in general.

In response to the impact of these emissions IMO is also tightening the emission limits for NOx and SOx. First, IMO has defined the coast around North America and the North Sea and the Baltic as Emission Control Areas (ECA) with stricter SOx rules beginning in 2015, i.e. 0.1% and globally with stricter Sulphur rules from 2020, i.e. 0.5% as illustrated by Figure 2 below. Second, IMO requires that new-built vessels, beginning in 2016, that plan to operate in the North American ECA shall reduce their NOx emissions by 75%, measured in gram per kWh, compared to the IMO tier II standard for vessels built after 2011 as illustrated by Table 2 (below). For the artic, IMO in close partnership with the arctic nations is developing a polar code that will be mandatory for all vessels that plan to operate in arctic areas. The code will address the all aspects of operating in the arctic including navigation, communication and accident avoidance, groundings and leakage of fuel or cargo to the arctic environment. Air emissions are expected to be included in the polar code at a later stage.

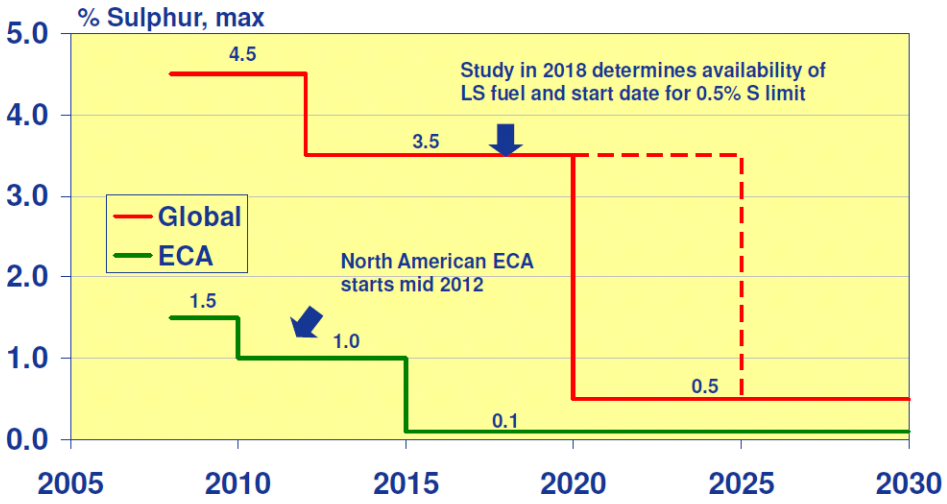


Figure 2: Fuel sulphur requirements, world-wide and in Sulphur Emission Control Areas (SECA)

Table 2: NOx emission limits in g/kWh: * IMO Tier III NOx from 2016 for the North American ECA. It might be adopted in Europe later.

NO_X emission limits [in g/kWh]	**Tier I**	**Tier II**	**Tier III**
Year	**2005**	**2011**	**2016***
NO_X Emission Control Area (NECA)			2.0 - 3.4
Worldwide**	9.8 – 17	7.7 - 14.4	

2.3 Historical Development of Trade and Maritime freight

From the first days of our civilization sea transport has dominated trades between nations, regions, and continents. World trade in the form we know today started in the middle of the 19th century as global communication developed with steam engines allowing vessels to move without wind, steel hulls enabling larger ships, screw propellers making ships more seaworthy and deep-sea cables allowing traders and ship owners to communicate across the world [Stopford, 2009]. In combination with the industrialisation of the West in the 19th century and its dominance in the rest of the world [Harlaftis and Theotokas, 2002], this enabled a strong growth in trade and transport which continued during the 20th century. Transport is one of the four cornerstones of globalisation. Together with telecommunication, trade liberalisation and international standardisation, the increased efficiency of maritime transport has enabled the globalization of the world [Kumar and Hoffman, 2002].

Globalization means that trade is growing faster than the global gross domestic product (GDP). This trade is not only in finished goods and services, but increasingly in components and services that are used within globalized production process [ECLAC, 2002]. It is therefore of importance to understand why we have trade and what drives trade. Table 3 illustrates the strong globalisation of the world from 1950 up to 2010 [Lindstad, 2013].

Table 3: Global population, energy consumption, GDP, transport and trade from 1950 to 2010 with all monetary figures adjusted to 2010 levels. Sources UNCTDAD, 2014, Lindstad, 2013, IEA, 2014, Madison, 2007.

Year		1970	1980	1990	2000	2010	2012	1970-2012 Increase
Population	(Million)	3 700	4 500	5 300	6 000	6 900	7 000	89%
Energy consumption	(Million TOE)	4 900	6 600	8 100	9 400	12 000	13 300	171%
Maritime transport	(Million Ton)	2 600	3 700	4 000	6 000	8 000	9 200	254%
Gross domestic product - GDP	(Billion USD)	15 500	22 400	30 600	40 300	52 000	54 700	253%
Freight work by Maritime transport	(Billion Ton nautical miles)	12 600	19 800	18 700	26 800	42 200	46 200	267%
World Trade	(Billion USD)	1 400	3 500	5 400	8 100	15 000	18 000	1186%
Word Trade as share of GDP		9%	16%	18%	20%	29%	33%	

Main observations from the table are the following:

- energy usage has increased 2 times faster than the population growth,
- maritime transport (in Million ton) has increased 2 times faster than the GDP growth and 3 times faster than the growth in energy consumption
- World trade has increased 5 times faster than GDP growth.

More interesting than the increase in transported tonnage, is the increase in freight work (in ton-nautical miles).

The increase of the actual freight work from 1970 to 2010 based on recent UNCTAD figures published in the IMO 2014 GHG study (Tristan et al., 2014). In Table 4 the freight work figures are combined with the development of the global GDP from 1970 to 2010. Freight work is here totalled as sum of: dry bulk excluding coal; coal; other dry cargo; oil transport (Crude & Products); other cargo (chemicals, LNG, LPG, other liquids.

Table 4: Development of freight work and Global GDP in billions over the last decades since 1970

Year		1970	1980	1990	2000	2007	2010	2012
Total Dry Bulk except coal	ton nm	1 900	3 000	3 500	4 300	7 200	8 300	9 200
Coal	ton nm	600	900	1 900	2 400	3 900	4 400	5 000
Other Dry cargo	ton nm	2 200	3 500	3 900	7 400	12 400	12 600	14 400
Total oil transported	ton nm	6 500	10 200	7 200	9 600	11 500	11 600	12 200
Other Cargo	ton nm	1 500	2 300	2 200	3 200	4 400	5 300	5 400
Freight Work	ton nm	12 600	19 800	18 700	26 800	39 300	42 200	46 200
Global GDP constant 2005	USD	16 200	23 100	32 300	41 500	52 300	53 900	56 900
Freight increase from 1970			58%	49%	113%	213%	236%	268%
GDP increase since 1970			43%	100%	157%	224%	233%	252%
Freight increase/ GDP Increase accumulated			135%	49%	72%	95%	101%	106%
Freight increase/ GDP Increase per decade			110%	-15%	153%	180%	194%	163%

From Table 4, it can be seen that in the last four decades, GDP increase and freight increase developed similarly. Over the years, the relationship freight increase to GDP increase have been 1.17, 0.09, 1.20 and 1.63, respectively for the periods 1970-1980, 1980-1990, 1990-2000 and 2000-2010. A number larger than 1 means that sea freight work has increased faster than GDP. This indicates that the general assumption that sea transport freight work only increases with 80% of the growth in sea transport might not be correct and that it should be 100% or larger instead. It should be noted that coastal national transport between domestic ports or crude by shuttle tankers to land terminals domestically has been excluded from Table 3 and 4 while they are included in all other tables.

The table above shows that GDP growth can indeed be used as proxy to forecast freight work in the years 2030. This methodology is in line with the second IMO study [IMO, 2009] and therefore provides comparable results for trade and maritime transport flows. The main difference is that the IMO 2009 GHG study used the assumption that sea freight work increases with 80% of GDP, while a one to one relationship is more in line with the historical development from 1970 to 2012. The explanation is that the freight work has increased by 6% more than the growth in GDP and not by a lower amount corresponding to the 80% relationship. In this study we have therefore chosen to use a one to one relationship between growth in the GDP and freight as the basis for the baseline and the reference scenario.

2.4 Historical Development of fleet, vessel types and operational pattern

The first version of the third IMO 2014 GHG study (Tristan et al 2014) was published in august 2014.

It follows the first GHG study which was published in 2000 and the second GHG study which was published in 2009. The First IMO GHG Study (Skjølsvik et al., 2000) estimated that ships engaged in international trade in 1996 contributed about 1.8% of the world total anthropogenic CO_2 emissions. The *Second IMO 2009 GHG study* (Buhaug et al 2009) which estimated that ships engaged in international trade in 2007 contributed about 2.7% of the world total anthropogenic CO_2 emissions, and that ships in total contributed 3.3%.)

Based on the IMO studies, a projection is made of the CO_2 emissions per vessel segment for 2012. This is presented in Table 5, which shows development of number of vessels, average vessel size, design speed and average speeds and the total emissions per vessel type from 2007 to 2012. The 2007 totals are directly from the IMO 2009 GHG study.

The totals show that emissions from the cargo carrying fleet were reduced with 8% while emissions from other vessel types were reduced by 31%. The total GHG emissions were reduced between 2007 and 2013 by 13%, from 1.095 billion ton CO_2 to 0.949 billion ton CO_2.

In Table 6, these figures have been combined with UNCTAD freight work statistics for the same years. Main observations which can be made are:

- freight work has increased by 18% from 41 000 to 48 000 billion ton nm (2007-2012);
- capacity measured in dwt has increased by 50%;
- average speed is reduced from 12.0 to 11.1 knots for the cargo carrying fleet.

As a result, regarding CO_2 reduction,

- larger vessels has given an economy of scale effect contributing to a 5.5% CO_2 reduction per ton nm;
- change in fleet mix and size (i.e. a larger share of the fleet is dry bulkers which has a high average dwt) has contributed with 4.5% reduction;
- average speed reduction has contributed to a 16% reduction in emissions per ton nm.

In total, the CO_2 per ton nm has been reduced with 25%.

It can be concluded that the explanation for the CO_2 reduction are: economies of scale; change in fleet mix; and operational speed reduction.

Table 5: Key numbers from IMO 2014 GHG Study [IMO, 2014] per vessel type

Vessel type	Number of vessels 2007	Number of vessels 2012	Average vessel size in dwt 2007		Average vessel size in dwt 2012	Design Speed 2007	Design Speed 2012	Average Speed 2007	Average Speed 2012	CO2 2007 IMO 2009 GHG-Study	CO2 2007	CO2 2012	Change in CO2 2007 - 2012
			ton		ton	knots	knots	knots	knots	ton	ton	ton	%
Dry Bulk	7 523	10 395	52 500		68 600	14.1	14.8	12.2	11.5	170 000	179 000	166 000	-7%
General Cargo	17 280	16 486	4 600		5 300	12.1	12.5	10.0	9.3	93 000	100 000	70 000	-30%
Container	4 398	5 132	34 200		41 600	20.3	21.3	16.3	14.6	241 000	206 000	205 000	
Reefer	1 226	1 090	5 400		5 700	16.2	16.2	16.3	13.4	19 000	20 500	18 000	-12%
RoRo & Vehicle	2 410	2 585	7 200		7 600	16.3	16.3	15.0	15.0	42 000	56 000	56 000	
OilTanker-mainly crude > 80' dwt	1 569	1 991	176 500		183 500	15.5	15.7	13.8	11.9	91 000	106 000	80 000	-25%
OilTankers-mainly product < 80'dwt	5 390	5 404	9 800		13 300	12.3	12.4	10.6	9.4	54 000	44 000	45 000	2%
Chemicals	3 868	4 935	15 800		18 000	13.4	13.6	12.1	11.1	53 000	58 000	55 000	-5%
LNG & LPG	1 368	1 612	22 800		27 600	14.9	15.6	13.1	12.9	38 000	32 000	50 000	56%
RoPax	2 784	2 867	1 400		1 600	17.9	16.6	13.8	10.7	61 000	46 000	32 000	-30%
Totals Cargo Vessels	47 816	52 497	22 500		30 800	14.1	14.6	12.0	11.1	862 000	847 500	777 000	-8%
Ferry-Pax only	3 019	3 152	100		170	23.5	22.6	18.7	13.8	17 000	19 200	12 000	-38%
Cruise	489	520	3 200		3 700	17.0	17.2	12.5	12.0	19 000	34 000	35 500	4%
Yacht	1 162	1 750	80		170	17.1	16.5	12.6	10.7	2 500	3 300	3 500	6%
Offshore	5 204	6 480	1 600		1 700	13.4	13.8	9.7	8.0	20 000	36 000	28 000	-22%
Service	17 808	18 064	490		540	12.0	12.0	8.7	7.5	52 000	53 600	34 000	-37%
Fishing	23 643	22 130	240		180	11.8	11.5	9.7	7.4	63 000	86 100	51 500	-40%
Other	1 169	3 008	1 100		60	11.3	12.7	8.7	7.3	10 500	15 300	7 500	-51%
Totals Other Vessels	52 494	55 104	480		530	12.9	12.9	10.0	8.1	184 000	247 500	172 000	-31%
Totals All Vessels	100 310	107 601	11 000		15 300	13.5	13.7	10.9	9.5	1046 000	1095 000	949 000	-13%

Table 6: Data of earlier IMO studies combined with UNCTAD freight work statistics

Vessel type	Average vessel size in dwt		Freight work		Market share of freight work		DWT Capacity Increase at equal speeds 2007-2012	Emission change due to reduced sea speeds	Emission change due to EOS	Emission Change due to developmt of fleet mix and size distribution	CO2 - per ton nm		Change in CO2 per ton nm 2007 - 2012	Change in CO2 if operated at design speed 2007 - 2012	
	2007	2012	2007	2012	2007	2012					2007	2012			
	ton		Billion ton nm								Gram/ton nm				
Dry Bulk	52 500	68 600	16 000	20 000	39.0%	41.7%	81%	-12%	-8.5%		7.0	8.4	-19%	1%	
General Cargo	4 600	5 300	2 400	2 300	5.9%	4.8%	2%	-14%	-4.6%		25.5	30.0	-18%	2%	
Container	34 200	41 600	7 500	9 000	18.3%	18.8%	42%	-20%	-6.3%		18.4	23.0	-25%	3%	
Reefer	5 400	5 700	250	225	0.6%	0.5%	-6%	-32%	-1.8%		60.2	80.4	-34%	-2%	
RoRo	7 200	7 600	500	550	1.2%	1.1%	13%	0%	-1.8%		98.1	99.8	-2%	-2%	
OilTanker-mainly crude > 80' dwt	176 500	183 500	9 500	10 000	23.2%	20.8%	32%	-26%	-1.3%		6.3	8.0	-27%	1%	
OilTankers-mainly product < 80'dwt	9 800	13 300	1 700	2 000	4.1%	4.2%	36%	-21%	-9.7%		17.3	22.3	-29%	-9%	(1)
Chemicals	15 800	18 000	1 900	2 300	4.6%	4.8%	45%	-15%	-4.2%		20.4	24.3	-19%	-1%	
LNG & LPG	22 800	27 600	1 100	1 500	2.7%	3.1%	43%	-3%	-6.2%		30.7	33.4	-9%	3%	
RoPax	1 400	1 600	150	125	0.4%	0.3%	18%	-40%	-4.3%		177.5	252.8	-42%	-18%	(2)
Totals Cargo Vessels	22 500	30 800	41 000	48 000	100%	100%	50%	-16%	-5.5%	-4.5%	20.7	16.2	-25%		

(1) 35 % increase in size (2) 25 % decrease of average speed

2.5 European emissions

The share of CO_2 emissions which can be attributed to European maritime transport was evaluated in two earlier studies. This was done in the 2009 technical support study for the European Commission (CE Delft 2009) and the Impact assessment study (AEA-Ricardo, 2013). CO_2 emissions related to Europe of these studies are presented in respectively table 7 and 8 below. The CE Delft study was based on 2006/2007 trading patterns and was done in close partnership with the Second IMO GHG Study (Buhaug et al 2009) which used 2007 as the reference year. Total 2007 global maritime emissions were quantified to be 1046 million tons, which implies that the European share of the emissions was 25 – 28 %. The Richardo - AEA study based on 2010 AIS data shows lower European emissions 20 – 25 % (uncertainty regarding total global emissions). Since then World trade has increased, i.e. more Intra Asian and trades between Australia and North East Asia. Based on this we estimate the current European maritime emissions to be around 20% of the total global one.

Table 7: CO_2 emissions of maritime transport attributed to Europe, year 2006. Source CE Delft, 2009

Region of origin or destination	**Ships arriving in Europe this region**			**Ships leaving Europe to this region**		
	Fuel use (Mt)	**CO_2 emissions (Mt)**	**Percentage of total CO_2 emissions %**	**Fuel use (Mt)**	**CO_2 emissions (Mt)**	**Percentage of total CO_2 emissions %**
North America	5	15.9	6%	5.6	17.7	6%
Central America	1.9	5.7	2%	1.8	5.3	2%
South America	3.3	10.5	4%	4.3	13.9	5%
Africa	6.7	21.2	8%	5.9	18.5	7%
Middle East	1.7	5.5	2%	2.5	7.8	3%
Indian subcontinent	0,8	2.6	1%	0.8	2.6	1%
Far East Asia	3,7	11.6	4%	4.3	13.3	5%
North East Asia	1.3	4	1%	2	6.2	2%
Oceania	0.6	1.9	1%	0.2	0.6	0%
Euro	63.5	197.7	71%	63.5	197.5	70%
Total Europe	**88.5**	**276.6**	**100%**	**90.9**	**283.4**	**100%**

Table 8: Effects of different carbon trading schemes on European CO_2 emissions. Source AEA-Ricardo, 2013.

Scenario	**Maritime sector emissions (annual $MtCO_2$)**	**Maritime sector emissions reductions compared to baseline ($mtCO_2$)**	**Out of sector permit purchase ($MtCO_2$)**	**Net total emissions**	**Percentage change compared to 2005 emissions**	**Cumulative emissions reductions 2015-2030**
Baseline	223.41	-	-	223.41	+14.6%	-
Shipping ETS – closed with free allocations	175.74	47.67	-	175.74	-9.9%	-377.07
Shipping ETS – open with free allocations	186.73	36.68	10.99	175.74	-9.9%	-333.80
Shipping ETS – open with full allocations	186.76	36.65	11.03	175.74	-9.9%	-336.27
Tax on emissions (low)	186.75	36.66	-	186.75	-4.2%	-335.35
Tax on emissions (high)	176.09	47.32	-	176.09	-9.7%	-390.30
Target based compensation fund	186.76	36.65	11.03	175.74	-9.9%	-336.27
Contribution based compensation fund	186.75	36.66	-	186.75	-4.2%	-335.35

3. Reference scenario [task 2]

3.1 Objective task 2

The objective of task 2 of the project was twofold:

- Establish a reference scenario for GHG emissions from maritime transport up to 2030.
- Conduct a sensitivity analysis regarding the main drivers that are identified in Task 1 of the project.

3.2 The Emission Scenarios and modelling

Four scenarios for the development up to 2030 have been defined in order to structure the work and to show the influence of key drivers and model parameters.

The four scenarios, which are all based on the same growth of freight work (refer to section 2.3), are the following:

1. Baseline:
   CO_2 emissions with 2012 fleet characteristics (vessel size and efficiency).
2. EOS – Economy of Scale:
   CO_2 emissions with the expected growth in vessel sizes
3. BAU – Business as Usual:
   CO_2 emissions with EOS and EEDI implemented
4. Reference scenario:
   CO_2 emissions including EOS, EEDI and fuel change (LNG)

In order to estimate the emissions in the year 2030, a model has been developed that incorporates the key drivers discussed above. A schematic of the modelling approach is shown in Figure 3.

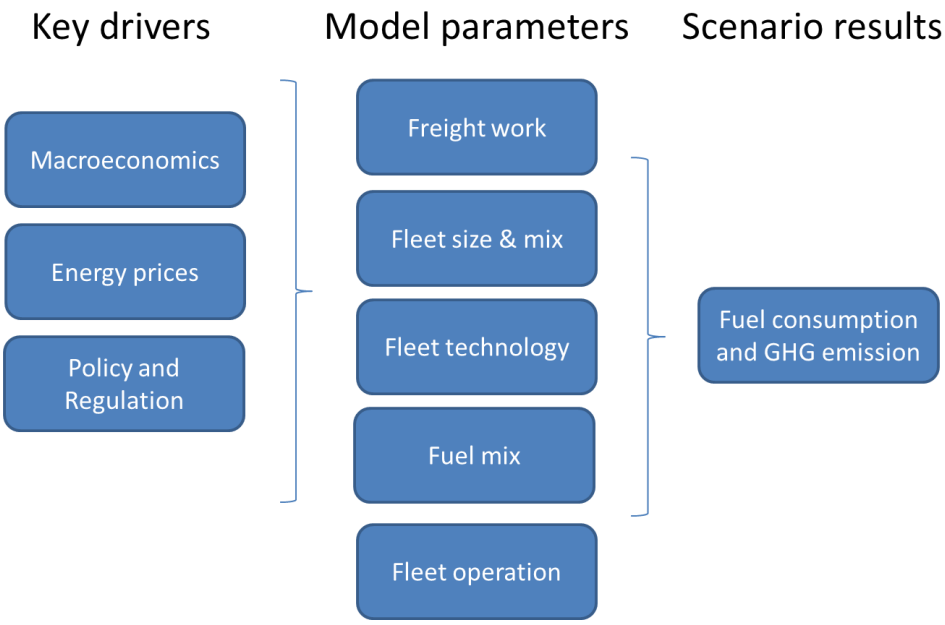


Figure 3: Schematic of the modelling approach

3.3 Trade and Emission Development up to 2030

3.3.1 *GDP growth and Development of freight workup to 2030*

Predictions of future GDP growth are available from a number of sources and common for all of them is that there are uncertainties. This study uses the latest IPCC Shared Socioeconomic Pathways (SSPs) and related Integrated Assessment scenarios as baseline for the expected GDP growth until 2030. The data for these new socio-economic and environmental scenario and the results of IAMs runs with emissions and energy use developments can be downloaded from IIASA's homepage [IIASA, 2014] and it has a country dimension. The data includes GDP growth rates, detailed population forecast and urbanisation forecast. In this study, the 'SSP 2 - Middle of the Road' scenario (meaning Dynamics as Usual, or Current Trends Continue, or Continuation, or Muddling Through) is used as baseline for GDP growth. The effective freight work for 2030 is calculated as shown in Table 9 using an annual growth rate of 4.25% and the one to one relationship (see section 1.3).

Table 9: Freight work, 2012 compared to 2030

Vessel type	**Freight work**	
Units	**[billion ton nm]**	
Year	**2012**	**2030**
Dry Bulk	20000	42400
General Cargo	2400	5100
Container	9000	19100
Reefer	225	500
Ro-Ro & Vehicle	550	1200
Oil Tanker (dwt>80000) - mainly crude	10000	21200
Oil Tanker (dwt<80000) - mainly product	1950	4100
Chemicals	2250	4800
LNG & LPG	1500	3200
RoPax	125	300
TOTAL, Cargo	**48000**	**101900**
Ferry-Pax only	10	20
Cruise	20	40
Yacht	0	0
Offshore	140	280
Service	90	180
Fishing	50	100
Other	**20**	**40**
TOTAL, Other	330	660
TOTAL, All	**48330**	**102560**

Based on the growth rates provided in the IPCC Shared Socioeconomic Pathways (SSPs), the freight work is expected to double from 2012 to 2030. The increase in freight work is expected to be evenly distributed across vessel the types. This assumption could be debated, however more than 80% of the total freight work is performed by the Dry bulkers, the Container vessels and the Oil tankers. This means that if additional analysis is required the resources should be focused on these three vessel types. For crude oil a continued growth in freight work may not happen, due to upcoming other energy sources such as wind-, solar- and biofuel energy and the continued focus on improvements of energy efficiency of all energy consumers. For this reason, within the sensitivity analysis (section 2.6), a sensitivity is done assuming a constant volume of freight transport for crude oil between 2012 and 2030.

3.3.2 *Predictions for vessel size and fleet development*

In the IMO 2014 GHG study the focus was on the development from 2007 to 2012. In this study the objective is to make predictions from 2015 up to 2030. To make such predictions we use a reference period from 2002 to 2015 to enable a better prediction for how the fleet development will be up to 2030.

Table 10 shows how average vessel size has increased from 2002 to 2015 per vessel type. Specific data regarding the development for different cargo and other vessel categories is included in Appendix A.

Table 10: Development of average vessel size 2002 - 2015

Vessel type	Average vessel size in dwt				Increase
	2002	2007	2012	2015	
Dry Bulk	49 200	52 500	68 600	69 300	41%
General Cargo	5 800	4 600	5 300	6 200	7%
Container	25 600	34 200	41 600	44 300	73%
Reefer	5 400	5 400	5 700	6 000	11%
RoRo & Vehicle	7 200	7 200	7 600	8 900	24%
Oil Tanker -above 80'dwt mainly crude	182 800	178 700	182 700	185 800	2%
Oil Tankers -bellow 80'dwt mainly product	9 800	9 800	10 700	10 700	9%
Chemicals	12 400	15 800	18 000	19 000	53%
LNG & LPG	18 300	22 800	27 600	29 000	58%
RoPax	1 400	1 400	1 600	1 800	29%
Cargo Vessels	20 100	22 500	30 500	31 500	57%
Ferry-Pax only	100	100	170	170	70%
Cruise	3 200	3 200	3 700	4 000	25%
Yacht	80	80	170	170	113%
Offshore	1 600	1 600	1 700	1 700	6%
Service	490	490	540	540	10%
Fishing	240	240	180	180	-25%
Other	1 100	1 100	1 100	1 100	0%
Other Vessels	540	540	560	570	6%
All Vessels	12 100	12 800	15 200	15 600	29%

From 2002 to 2015, the average cargo vessel size has increased from 20100 to 31500 ton. The increase of average size has been largest for the containers, i.e. 73% versus only 2% for the crude oil carriers. For passenger vessels and vessels built for other purposes such as offshore, service and fishing the average vessel has increased only marginally, i.e. from 540 to 570 tons.

The main reason why vessel size is increasing is that, larger ships tend to be more energy efficient per freight unit than smaller vessels. With the enlargement of primarily the Panama Canal but also for some vessel type the Suez-Canal, this size increase is expected to be continued in the future. This is also reflected in the current order book of the shipyards (ISL 2014).

It is expected that the average vessel size increase for the period 2015 to 2030 will be about the same as for the period from 2002 to 2015. The average vessel sizes in 2030 will then be as shown in Table 11. By combing these figures with the expected increase in freight work as specified in Table 9 and assuming that days at sea, capacity utilization and speed stays constant, the number of vessels per vessel type can be calculated by multiplying the 2015 fleet by the expected growth in freight work and divide on the expected increase in size. This gives a 2030 fleet as shown in Table 11.

Table 11: Number of vessels and average vessel sizes, 2015 compared to 2030

Vessel type	Vessel size in dwt		Number of vessels		Freight work	
	2015	2030E	2015	2030E	2015E	2030E
Dry Bulk	69 300	98 000	11 200	15 300	22 000	42 400
General Cargo	6 200	7 000	17 000	29 500	2 600	5 100
Container	44 300	77 000	5 600	6 200	9 900	19 100
Reefer	6 000	7 000	1 050	2 300	200	500
RoRo & Vehicle	8 900	11 000	2 600	4 200	600	1 200
Oil Tanker -above 80'dwt mainly crude	185 800	189 000	2 400	4 500	11 000	21 200
Oil Tankers -bellow 80'dwt mainly product	10 700	12 000	5 400	9 400	2 100	4 100
Chemicals	19 000	29 000	5 400	6 800	2 500	4 800
LNG & LPG	29 000	46 000	1 800	2 100	1 700	3 200
RoPax	1 800	2 300	2 308	5 400	100	300
Average Cargo Vessels	31 500	42 500	54 800	85 700	52 700	101 900
Ferry-Pax only	170	200	3 300	5 600	10	20
Cruise	4 000	4 800	550	900	20	40
Yacht	170	200	1 750	1 750	0	0
Offshore	1 700	1 800	6 500	6 500	140	150
Service	540	600	18 100	18 100	90	100
Fishing	180	180	22 100	22 100	50	50
Other	1 100	1 100	3 000	3 000	20	20
Average Other Vessels	570	600	55 300	60 500	330	380
All Vessels	15 600	19 500	110 100	146 200	53 000	102 300

Main observations are: the average size of cargo vessels increases from 31 500 to 42 500 dwt; the average size of other vessels increases from 570 to 600 dwt; the cargo carrying fleet increases from 54' to 85' vessels while there is only a marginal increase for other vessels. Based on the age distribution in the fleet, where the oldest vessel in general are smaller than the newer ones and since the order book for new buildings is dominated by larger vessels, it might that an 2030 average size of 42 000 tons is rather in the low than in the high range. In contrast, it should be noted that the IMO 2014 GHG study [IMO, 2014] concludes, based on a qualitative assessment, that average vessel sizes will only increase marginally from 2012 to 2050. We question this assessment. The consequence of using the IMO 2014 GHG study assumption would be that the cargo carrying fleet doubles already in 2030, which is not realistic.

3.3.3 *Influence of EEDI on CO_2 emissions*

The technical options for satisfying the EEDI requirements is basically to reduce the required energy to achieve the desired design speed, or to reduce the design speed and hence the required installed power. Traditionally the design focus of sea going vessels such as bulkers and tankers has been on maximizing cargo carrying capability at the lowest building cost, and not on minimizing energy consumption per transported unit. The outcome has been shoebox-shaped vessels with short bow and aft sections and hence rather poor hydrodynamic lines and high resistance even at calm seas. In rough sea these design performs even worse compared with vessels with the same cargo carrying capability designed for good hydrodynamic performance. Lindstad et al 2013, Lindstad 2013, Lindstad et al 2014 and Lindstad and Eskeland (in progress) 2014 has challenged this approach and investigated cost and emissions as a function of alternative bulk vessel designs with focus on a vessel's beam, length and hull slenderness expressed by the length displacement ratio for three fuel price scenarios. The results show that when the block coefficient is reduced and the hull becomes more slender the emissions drop. Table 12 shows some typical block coefficients

Table 12: Typical parameters including block coefficients for different vessel categories

	Dead weight - Dwt	Length - lpp	Beam	Block coeficient	Service speed	Engine size
RoRo deep sea large car carrier	30 000	218	32.3	0.60	20.0	16000
Cont - 12 000 TEU	155 000	370	56.0	0.63	25.0	80000
Cont - 2000 TEU	30 000	190	30.0	0.64	22.0	28000
RoRo deep sea large & heavy cargo	42 500	250	32.3	0.64	20.5	22000
LPG - 50 000 dwt	52 000	222	37.2	0.74	17.0	14000
LNG - 80 000 dwt	80 000	270	43.4	0.76	19.5	39000
General Cargo 20 000 dwt	20 000	150	23.0	0.79	16.0	9000
Dry Bulk Capesize - Newcastle	208 000	295	50.0	0.84	15.0	19000
Crude oil 115 000 dwt	115 000	240	44.0	0.84	15.0	14000
Products-chemical tanker Panamax	75 000	219	32.2	0.85	15.0	11000
Crude Panamax	77 000	220	32.3	0.86	15.0	12000
Dry Bulk Panamax	80 000	220	32.2	0.87	14.5	9800

For emissions the results demonstrate that making vessels more slender gives lower emissions per freight unit transported and that the more slender the vessels becomes, the better their EEDI performance becomes. The most slender of these designs over performs with 25 – 35% compared to today's EEDI thresholds as illustrated by Lindstad et al (2014) in figure 4 , which actually means that they might satisfy foreseen future requirements coming into effect the next 20 years.

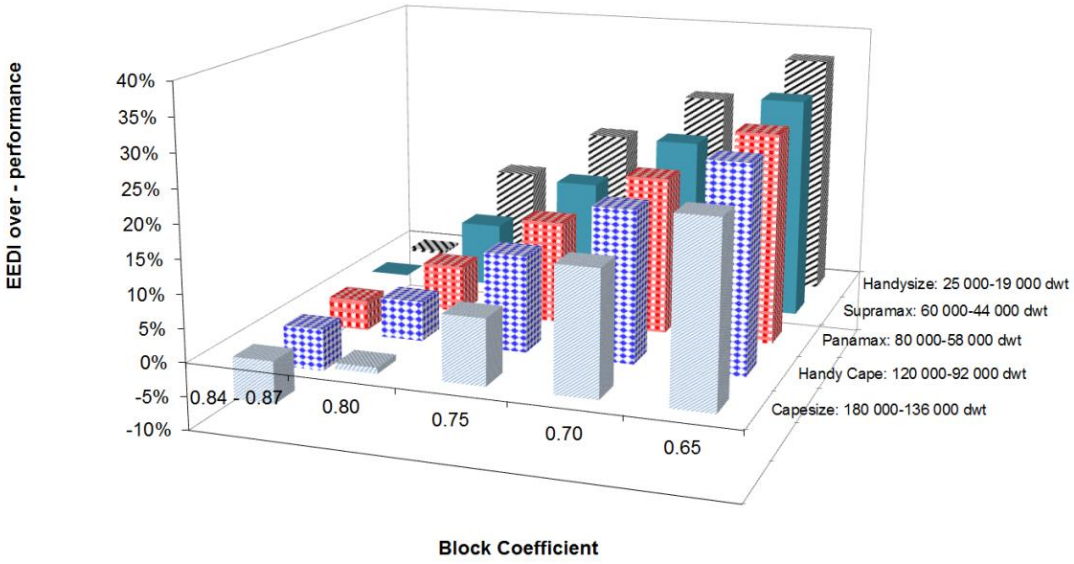


Figure 4: EEDI as a function of the block coefficient

The second technical options for satisfying the EEDI requirements is to reduce the design speed and hence the required installed power. However this will only contribute to reducing operational emissions measured by EEOI if the average operational speed of the vessels also is reduced, because if operational speed is kept similar emissions per ton nm will only marginally be affected by making the vessels 20% larger or 20% less. However what often is overlooked is that fact that bulkers and tankers needs their installed power to be seaworthy in rough weather (high sea states) which means that it is survival conditions which has decided the installed power and not the design speed as such. And since the survival condition for larger vessels is when the wave length equals vessel length and the additional power required is a function of the square of the wave amplitude it implies that the longer the vessel becomes the larger the power reserve has to be. Table 13 shows how installed power per dwt has developed from 2010 to 2015 for the individual ship types and ship sizes.

Table 13: Development of engine size and power per DWT between 2010 and 2015. Based on ISL data. Red indicates increase in kW per DWT.

	Average power main engines		Average DWT		Average kW per DWT		Ratio
	2010	2015	2010	2015	2010	2015	
Container average	23,561	27,688	35,229	44,305	0.669	0.625	93.4%
CONT_1_PPAN_up60	56,661	56,626	81,547	93,872	0.695	0.603	86.8%
CONT_2_PANA_60	32,121	33,761	48,907	49,867	0.657	0.677	103.1%
CONT_3_SPAN_40	21,363	21,818	34,866	34,888	0.613	0.625	102.1%
CONT_4_HAND_30	13,040	13,428	21,549	21,655	0.605	0.620	102.5%
CONT_5_FEEM_15	7,039	7,203	10,119	10,317	0.696	0.698	100.4%
CONT_6_FEED_5	2,366	2,517	3,268	3,710	0.724	0.679	93.7%
Dry Bulk average	8,466	9,516	58,973	69,038	0.144	0.138	96.0%
DB_1_BC_CAPE_up_120	16,127	18,165	182,262	195,145	0.088	0.093	105.2%
DB_2_BC_CAPE_85_120	12,038	12,735	94,057	97,308	0.128	0.131	102.2%
DB_3_BC_PANA_60_85	10,060	10,463	72,785	75,198	0.138	0.139	100.7%
DB_4_BC_HANM_35_60	8,427	8,738	47,288	50,175	0.178	0.174	97.7%
DB_5_BC_HAND_15_35	6,507	6,288	26,112	27,814	0.249	0.226	90.7%
DB_6_BC_COSTAL_0_15	2,151	1,962	5,138	4,921	0.419	0.399	95.2%
LNG & LPG average	10,025	10,759	27,255	29,032	0.368	0.371	100.8%
General Cargo average	2,652	2,633	5,671	6,244	0.468	0.422	90.2%
GC_1_up15	6,893	7,174	17,165	21,496	0.402	0.334	83.1%
GC_2_5_15	3,748	3,584	8,183	8,222	0.458	0.436	95.2%
GC_3_to_5	1,143	1,134	2,106	2,160	0.543	0.525	96.8%
RoRo & Vehicle average	8,212	8,680	8,651	8,927	0.949	0.972	102.4%
GC_RORO_1_up15	14,734	15,107	21,194	21,438	0.695	0.705	101.4%
GC_RORO_2_0_15	6,017	6,130	4,910	4,611	1.225	1.329	108.5%
Chemical tankers	4,972	5,282	17,328	19,016	0.287	0.278	96.8%
LB_CH_1_up_40	9,677	9,793	48,239	48,532	0.201	0.202	100.6%
LB_CH_2_15_40	7,766	7,583	27,035	26,354	0.287	0.288	100.2%
LB_CH_3_0_15	2,621	2,710	5,686	5,988	0.461	0.452	98.2%
Crude & Product tankers	7,348	8,365	56,256	63,998	0.131	0.131	100.1%
LB_CRPR_1_TK_ULCC	28,031	28,568	310,665	313,053	0.090	0.091	101.1%
LB_CRPR_2_TK_VLCC	20,266	20,363	202,397	197,038	0.100	0.103	103.2%
LB_CRPR_3_TK_SUEZ	13,475	13,725	108,853	109,579	0.124	0.125	101.2%
LB_CRPR_4_TK_AFRA	12,095	12,333	82,979	78,969	0.146	0.156	107.1%
LB_CRPR_5_TK_PANA	10,121	10,073	62,761	61,242	0.161	0.164	102.0%
LB_CRPR_6_TK_HAND	2,744	2,690	9,160	8,796	0.300	0.306	102.1%
Cruise average	30,606	33,061	4,921	5,264	6.220	6.281	101.0%
Ferry Pax only average	3,293	2,889	336	251	9.805	11.532	117.6%
RoPax average	7,949	7,432	1,808	1,752	4.396	4.243	96.5%

Main observations from the table is that installed power per kW has increased for 21 out of 32 vessel type/size combinations, but it has been significantly reduced for the larger container vessels. This is due to their reduced operational speeds since these vessels anyhow have more than enough power to be seaworthy in rough weather.

Historically the cost of fuel where low in comparison to the fixed and variable cost of the vessel. The lowest cost per transported unit where hence achieved by operating vessels at design speed (95% of maximum speed). More recently higher fuel prices have challenged this approach and speeds have been reduced.

However the speed has generally not been reduced down to the cost minimizing speed and one explanation is that the goods on board the vessels are an inventory which has to be financed similar to stocks in any other warehouse. Figure 5, based on Lindstad et al 2011, illustrates the shipping costs and CO_2 emission per ton nautical mile for large ocean going container vessels. This is based on a fuel price of 400 USD per ton (2011 prices), a cargo value of 5000 USD per ton and 5% interest.

Here the dotted lines include the cost of the vessel and the fuel, the dashed also includes the inventory cost of the goods on-board the vessel and the solid (emissions only) includes the CO_2 from building the vessels.

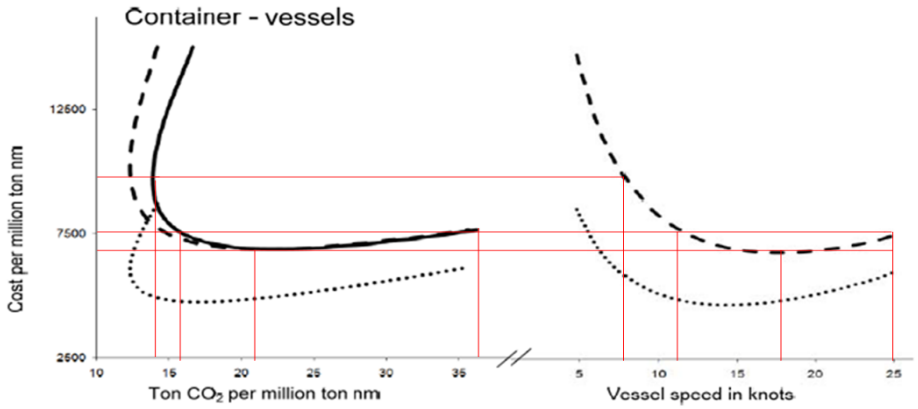


Figure 5: Shipping costs and CO_2 emission per ton nautical mile for a large container vessel. Dotted lines include vessel and fuel costs. Dashed lines include inventory costs as well. Solid line includes the CO_2 from building the vessel.

The main observations is that the cost minimizing speed is 18 knots, when the inventory cost for the goods on board is included, while it is 12–15 knots (from the dotted line), when we only consider the cost of the vessel and the fuel. Since 2011 the fuel price has increased from 400 to 600 which mean that the cost minimizing speed when the inventory cost is included has been reduced from 18 to around 15 knots.

In this study we have therefore made the assumption that 2012 average speeds reflects the new cost optimum speeds and that unless the ratios between vessel cost and fuel changes significantly, 2030 speeds will be in the same level as the 2012 speeds as shown in Table 14.

Table 14: Design speed and average vessel speed, 2012 compared to 2030

Vessel type	Design speed		Average speed	
Units	[knots]		[knots]	
Year	2012	2030	2012	2030
Dry Bulk	14.8	15.0	11.5	11.5
General Cargo	12.5	12.5	9.3	9.3
Container	21.3	23.0	14.6	14.6
Reefer	16.2	16.2	13.4	13.4
Ro-Ro & Vehicle	16.3	16.5	15.0	15.0
Oil Tanker (dwt>80000) - mainly crude	15.7	15.7	11.8	11.8
Oil Tanker (dwt<80000) - mainly product	12.4	12.5	9.4	9.4
Chemicals	13.6	14.0	11.1	11.1
LNG & LPG	15.6	17.0	12.9	12.9
RoPax	16.6	17.0	10.7	10.7
Average, Cargo Vessels	**14.6**	**14.6**	**11.1**	**11.1**
Ferry-Pax only	22.6	22.6	13.8	13.8
Cruise	17.2	17.2	12.0	12.0
Yacht	16.5	16.5	10.7	10.7
Offshore	13.8	13.8	8.0	8.0
Service	12.0	12.0	7.5	7.5
Fishing	11.5	11.5	7.4	7.4
Other	12.7	12.7	7.3	7.3
Average, Other Vessels	**12.9**	**12.9**	**8.1**	**8.1**
Average, All Vessels	**13.7**	**13.7**	**9.5**	**9.5**

3.3.4 *Influence of low sulfur fuels and LNG on CO_2 emissions*

The ECA and global fuel sulphur requirements will influence the CO_2 emissions up to 2030. The relevant steps as described in section 4.1 are:

- 2015: max 0.1% S fuel in ECA's
- 2020: max 0.5% S fuel global (outside ECA). This may be postponed until 2025

The fuel quality legislations are implemented to reduce the possible negative impact of maritime transport on air quality. In general, staying with diesel fuel, there would be a slightly negative impact on Well to Propeller GHG emissions when using lower sulphur diesel fuels. The additional fuel processing (de-sulfurization or distillation) does lead to extra energy consumption, which leads to slightly higher CO_2 emissions. On the other side, the specific CO_2 emissions of the fuel combustion (the tank to propeller emissions) will be slightly lower. Refer to Table 15 below: distilled fuels (MGO, MDO) have a lower CO_2 emission per MJ during combustion.

For GHG emissions of maritime transport, generally only the Tank to Propeller emissions is presented. In that case, the CO_2 emissions from a switch from HFO to MDO or MGO would show positive effects, while the Well to Tank emissions would actually increase somewhat. In order to avoid confusion, a constant factor for the specific CO_2 emissions is used for all diesel fuels; HFO, low sulphur HFO, MDO or MGO.

Table 15: TTW emission factors of CO_2 equivalent used for modelling

Fuel Type	Sulphur content	Methane emission	Energy content	TTP emission factor $CO_{2\ equivalent}$		
	[%S]	g/kWh	[MJ/kg]	[gCO_2/MJ]	[gCO_2/kWh]*	[$kgCO_2$/kg fuel]
HFO	~2.7%	□□	41.8	77	616	3.22
MDO	< 0.5%	-	42.5	74	592	3.15
MGO	< 0.1%	-	42.5	74	592	3.15
LNG	< 5-10 ppm	0	48.9	56	450	2.75
LNG low pressure	< 5-10 ppm	5 - 6	48.9	73	587	3.59
LNG high pressure	< 5-10 ppm	0.2 - 1	48.9	58	462	2.82
LNG 2030 average	< 5-10 ppm	3	48.9	66	525	3.21

* Per kWh mechanical energy based on engine efficiency of 45%

For LNG as a fuel, the potential CO_2 advantages are substantial, but this strongly dependent on the methane emission of the engine, also referred to as methane slip. This is graphically presented in Figure 6. In practise there is a considerable difference in methane emission depending on the engine type. Some engines have methane emissions of less than 1 g/kWh while others are close to 6 g/kWh [Verbeek, 2013]. Also refer to [Lindstad 2014]. For this study, for 2030 an average methane emission of 3 g/kWh mechanical engine work is used. For 2020 and 2025, an average methane emission of about 3.7 g/kWh is used. According to the official IPCC guidelines, for methane a GWP factor of 25 must be used for National GHG emissions inventories for Europe and for UNFCC reports (united Nations Framework Convention on Climate Change).
Using this factor 25 to calculate CO_2 equivalent emission, 3 g/kWh methane, increases the CO_2 equivalent emission by almost 10 g/MJ fuel energy (75 g/kWh mechanical energy). The Tank to Propeller CO_2 emission increases from 56 to about 66 g/MJ (or from 450 to 525 g/kWh) as shown in table 15. This corresponds to a Tank to Propeller CO_2 reduction of about 13% compared to HFO.

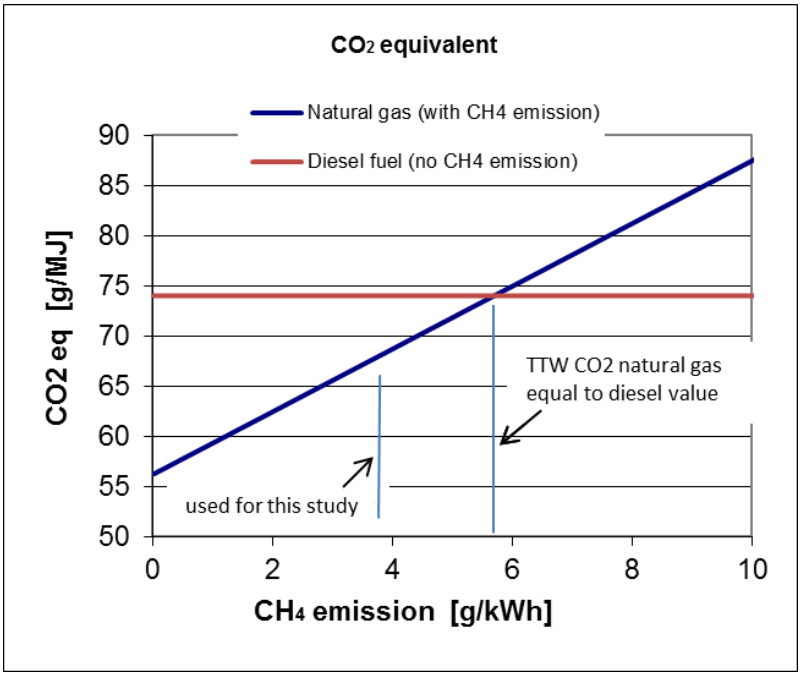


Figure 6: Comparison of GHG (CO_2 equivalent) emissions between diesel and natural gas engine as a function of methane emissions of the gas engine. Source: Verbeek et al, 2013.

3.4 Modelling results

As described in section 2.2, four scenarios with the 2030 freight work are modelled such that good insight is provided in the contribution of the main model parameters.

The scenarios are:

1. Baseline:
   CO_2 emissions with 2012 fleet characteristics (vessel size and efficiency).
2. EOS – Economy of Scale:
   CO_2 emissions with the expected growth in vessel sizes
3. BAU – Business as Usual:
   CO_2 emissions with EOS and EEDI implemented
4. Reference scenario:
   CO_2 emissions including EOS, EEDI and fuel change (LNG)

The results of the four scenarios per vessel category are presented in Table 16 below.

3.4.1 *Scenario 1: Baseline 2030*

Table 16 shows that the CO_2 emissions of the global maritime transport will increase from 0.95 billion ton in 2012 to a little over 2 billion ton in 2030 if this would be transported with the vessels of 2012. The number of vessels would need to increase by more than 100% to be able to transport the projected freight work for 2030.

3.4.2 *Scenario 2: Economy of Scale (EOS)*

Table 16 shows, that taking into account the expected growth in vessel size, the 2030 CO_2 emissions will total almost 1.8 billion ton in 2030. The number of vessels will then increase by some 75%. The EOS results in energy and CO_2 reductions of approximately 10% compared to the baseline (scenario 1).

3.4.3 *Scenario 3: BAU: EOS and EEDI*

In this scenario, the expected impact of EEDI is included.
When considering the effects of EEDI the following should be noted:

- 25% to 50% of the 2030 fleet was built before the introduction of EEDI
- Smaller vessels are exempted
- The EEDI targets are gradually becoming stricter
- Real life reduction of energy consumption will deviate from the EEDI improvements

Due to these points, an overall reduction of CO_2 emissions due to EEDI is expected in the range of 5 to 8% in 2030. This percentage will increase after 2030. The combined effect of EOS and EEDI for 2030 will be in the range of 15% to 18%.

3.4.4 *Scenario 4: Reference scenario*

In the reference scenario, in addition to EOS and EEDI also the LNG uptake is included. The influence is limited to about 1.5% CO_2 reduction for 2030 compared to scenario 3. The global CO_2 emissions are calculated to be in the range of 1.6 to 1.7 billion ton for 2030.

For most vessel categories an LNG share of 10% is projected for 2030, except for LNG and LPG carriers where a share of 50% (gas fuelled) is expected. The relative small influence is also due to the methane emissions of the LNG engines which reduces the potential GHG emission reduction for vessels running on LNG (max some 27%, used about 13%[4], refer to section 3.3.4). After 2030 the positive influence of LNG can increase when the market share increases and when engine improvements would lead to lower methane emissions.

[4] Based on Tank to Propeller emission

Table 16: Reference scenario: CO_2 emissions, 2012 compared to 2030, different scenarios.

Vessel type	Average vessel size in dwt		Baseline	Scenario 1 Baseline	Ratio due to EOS	Scenario 2 EOS	Ratio due to EEDI	Scenario 3 EOS + EEDI	Scenario 4: Reference: EOS + EEDI + LNG	
	2012	2030	2012	2030		2030		2030	LNG %	2030
Dry Bulk	68 600	98 000	166 000	351 900	0.89	312 500	0.90	281 250	10%	277 086
General Cargo	5 300	7 000	70 000	148 800	0.91	135 600	0.97	131 532	10%	129 585
Container	41 600	77 000	205 000	435 100	0.81	354 400	0.90	318 960	10%	314 238
Reefer	5 700	7 000	18 000	40 000	0.93	37 400	0.97	36 278	10%	35 741
RoRo & Vehicle	7 600	11 000	56 000	122 200	0.88	108 000	0.97	104 760	10%	103 209
Oil Tanker -above 80'dwt mainly crude	182 700	189 000	80 000	169 600	0.99	167 700	0.90	150 930	0%	150 930
Oil Tankers -bellow 80'dwt mainly product	10 700	12 000	45 000	94 600	0.96	91 100	0.97	88 367	0%	88 367
Chemicals	18 000	29 000	55 000	117 300	0.85	100 100	0.95	95 095	10%	93 687
LNG & LPG	27 600	46 000	50 000	106 700	0.84	90 000	0.95	85 500	50%	79 171
RoPax	1 600	2 300	32 000	76 800	0.89	68 000	0.97	65 960	10%	64 983
Cargo Vessels	30 500	42 500	777 000	1663 000	0.91	1464 800	0.93	1358 600		1337 000
Ferry-Pax only	170	200	12 000	24 000	0.95	22 700	0.97	22 019	10%	21 693
Cruise	3 700	4 800	35 500	71 000	0.92	65 100	0.97	63 147	10%	62 212
Yacht	170	200	3 500	7 000	0.95	6 600	0.97	6 402	0%	6 402
Offshore	1 700	1 800	28 000	56 000	0.98	54 900	0.97	53 253	10%	52 465
Service	540	600	34 000	68 000	0.97	65 700	0.97	63 729	10%	62 785
Fishing	180	200	51 500	103 000	0.97	99 400	0.97	96 418	0%	96 418
Other	1 100	1 100	7 500	15 000	1.00	15 000	0.97	14 550	10%	14 335
Other Vessels	560	600	172 000	344 000	0.98	329 400	0.97	319 500		316 300
All Vessels	15 200	21 000	949 000	2007 000	0.91	1794 200	0.94	1678 100		1653 300

3.4.5 *European reference scenario*

In two earlier studies, the CO_2 emissions which can be attributed to the European maritime transport were evaluated. Refer to section 2.5. The European share was determined to be approximately 20% of global transport. This factor is applied to the global CO_2 emissions of the previous sections for 2012. The future European economic growth rate projection is however lower than the world- wide growth rate of 4.25% annually (section 3.3.1). The European Aging report of DG Economic and Financial Affairs (EC, 2011) lists the expected future EU growth rates. The following numbers are listed in table 3.3 of the aging report:

Year	2010-2020	2021-2030
EA	1.3	1.5
EU27	1.5	1.6

Derived from this table, for this study an average GDP growth rate for Europe of 1.55% is used. This GDP growth rate is used for the baseline projection for Europe for 2012 to 2030.
The results, expressed in million ton per year are presented in Table 17 and Figure 7 below. This includes also the results for the intermediate years 2020 and 2025.

The results show that the annual CO_2 emissions will be around 250 million ton for European maritime transport for 2030. This is when doing about 30% more freight work than in 2012 with the same vessel size distribution and technologies as for 2012.

The reference scenario (scenario 4) includes the effects of the larger vessels (EOS), the effect of EEDI and the effect of LNG as a fuel. The projected CO_2 emissions for this scenario are just below 210 million ton.

The intermediate years are calculated using the corresponding freight work based on the yearly economic growth of 1.55%. The vessel size increase (EOS), EEDI and LNG are also phased in for the successive scenarios.

Table 17: CO_2 emission European maritime transport for 4 scenarios

Year	2012	2020	2025	2030
Million ton CO_2 per year				
Baseline	190	215	232	251
EOS	190	209	220	224
EOS + EEDI	190	206	213	210
Reference	190	205	212	208

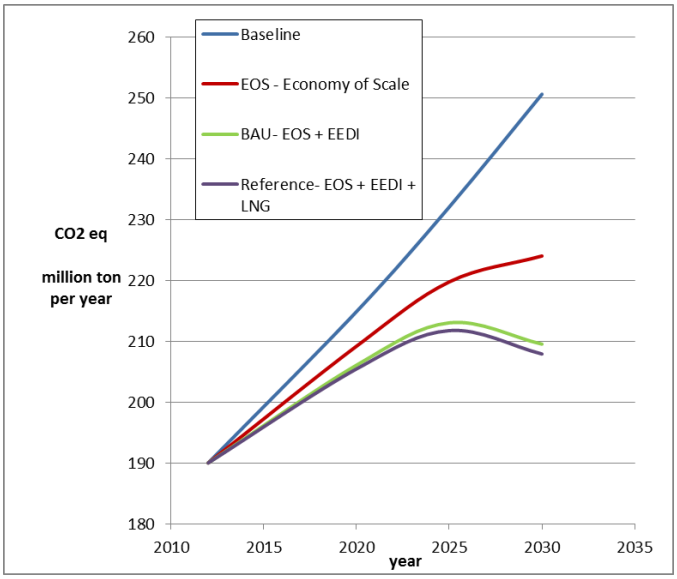


Figure 7: CO_2 emission European maritime transport for 4 scenarios

The following conclusions are made for the European maritime transport:

- Due to the increase in freight work of about 30% between 2012 and 2030, the annual CO_2 emissions are expected to increase from around 190 million ton in 2012 to just below 210 million ton in 2030 (reference scenario).
- The combined effect of larger vessels (EOS), implementation of EEDI and LNG as a fuel leads to a reduction of around 43 million ton CO_2 compared to the situation if the 2030 freight work would be transported with the 2012 vessel characteristics (size and efficiency). This corresponds to an efficiency increase of around 17% per ton nautical mile.

3.5 Sensitivity analysis

A sensitivity analysis is done with respect to the following main drivers:

- GDP growth
- EEDI implementation
- Implementation of LNG as a fuel
- Assuming a constant volume of freight transport for crude oil between 2012 and 2030.

The most important driver is the GDP growth. The effects of two additional GDP growth rates are calculated in addition to the average GDP growth of 1.55% annually, used for the previous scenarios:

- Low GDP growth: 0.77% annually (50% lower)
- High GDP growth: 2.32% annually (50% higher)

The annual growth rate of the freight work is the same as the one for economic growth (refer to section 3.3.1). The reference scenario is recalculated for this low and high GDP growth rates. The results are presented in Figure 8 below.

The figure shows the enormous influence of GDP growth rate. With the low economic growth rate of 0.77% annually, the annual CO_2 emissions will decrease from 190 million ton in 2012 to around 180 million ton in 2030. On the other side, if the GDP growth rate would increase by 50% (2.32% annually), the annual CO_2 emissions would increase to almost 240 million ton in 2030.

Also a large influence on annual CO_2 emission can be observed for keeping the freight work for crude oil constant between 2012 and 2030. This is because oil tanker transport is the third largest category with a CO_2 contribution of some 13% of the total. Keeping oil freight constant leads to an annual CO_2 reduction of some 17 million ton compared to the reference scenario (8% reduction).

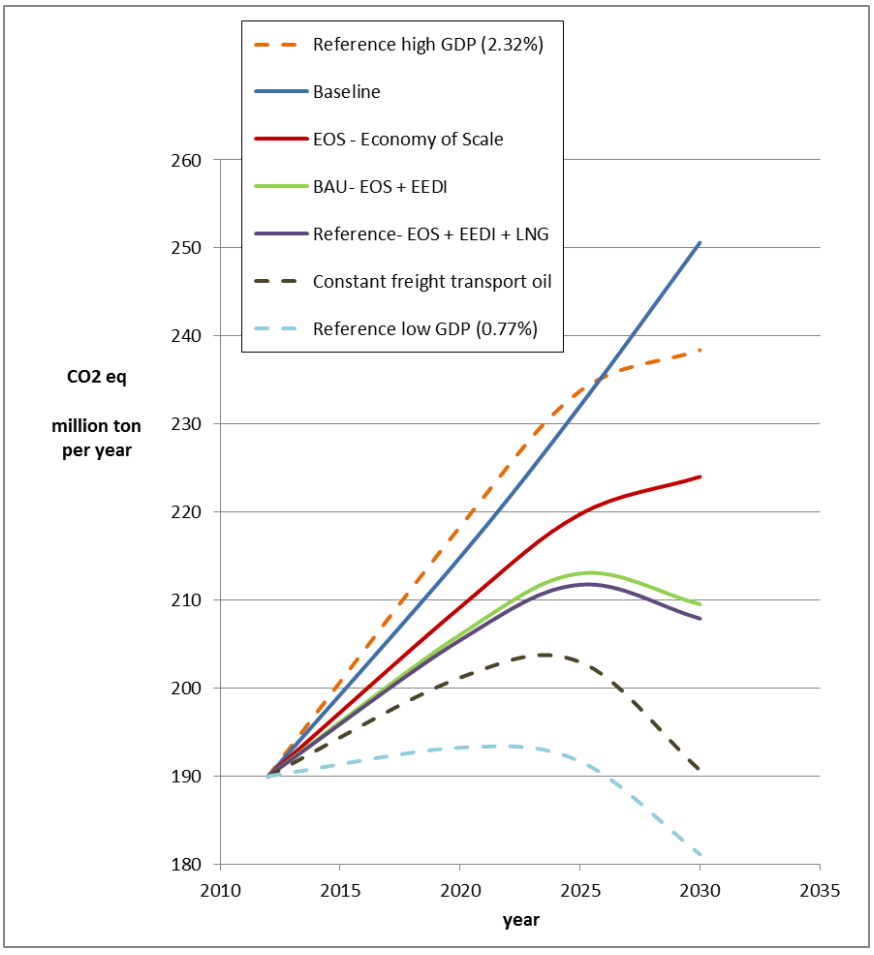


Figure 8: CO_2 emission European maritime transport, including scenarios for low and high GDP growth. Baseline GDP growth is 1.55%.

The influence of the other two main drivers is a lot smaller. Within the reference scenario, the EEDI lead to a CO_2 reduction of around 6%. This is taking into account that many ships were built before the entering into force of the EEDI and the expectation that the real world reduction will be lower than the EEDI reduction. This is mainly due to the expectation that the operation speeds are expected to remain about the same between 2012 and 2030. Refer to section 3.3.3, table 14.

The real life CO_2 reduction due to the EEDI could double for example due to more energy efficient designs, i.e. more slender designs. In that case, the CO_2 reduction due to EEDI could increase from around 6% to around 12%. This would mean an additional CO_2 reduction for the reference scenario of about 12 million ton annually.

In section 2.5, it was shown that LNG as a fuel has a relative small positive effect in 2030 of around 1.5%. Doubling the share of LNG within the fuel mix would lead to an additional 1.5% CO_2 emission reduction, which corresponds to around 3 million ton annually.

An overview of the sensitivity calculations is presented in Table 18 below.

Table 18: Results of sensitivity analysis on the total European CO_2 emissions.

	Reference 2012	Reference 2030	Sensitivity 2030
Million ton CO_2 per year			
Reference scenario	190	208	
High GDP growth rate			238
Low GDP growth rate			181
High EEDI contribution			196
High LNG penetration			205
Constant freight transport for oil			191

The following is concluded regarding the sensitivity analysis:

- The GDP growth rate has a dominant effect on annual CO_2 emissions. The 2030 European CO_2 emissions would increase from around 208 million ton to around 238 million ton annually, if the annual GDP growth rate would be 2.32% instead of 1.55%.
- A doubling of the EEDI influence would lead to a reduction of the CO_2 emissions of some 12 million ton annually.
- A doubling of the LNG fuel share (from around 10% to around 20%) would have a small effect and lead to an additional 1.5% CO_2 emissions reduction (3 million ton annually).
- Assuming a constant freight transport for crude oil between 2012 and 2030 (zero growth) leads to a CO_2 reduction of about 17 million ton annually (around 8%).

3.6 Conclusions

Task 2 of this maritime GHG study was focussed on the development of a reference scenario for maritime CO_2 emissions up to 2030. This includes the division of CO_2 emissions across a number of cargo and other vessel categories (in total about 17 categories).

A baseline for 2012 was based on the 2009 and 20014 IMO GHG studies.

Consequently 4 scenarios for 2030 were developed:

1. Baseline – GHG emission with 2012 vessel characteristics (size and efficiency)
2. EOS – GHG emission with the expected growth in vessel sizes
3. BAU – GHG emission with EOS and EEDI
4. Reference scenario - GHG emission with EOS, EEDI and fuel change (LNG)

For the reference scenario, CO_2 emissions of global maritime transport will increase from just below 1 billion ton in 2012 to approximately 1.65 billion ton in 2030. For the baseline (scenario 1) it would increase to around 2 billion ton in 2030.

The following conclusions are made for the European maritime transport:

- Due to the increase in freight work of more than 100% between 2012 and 2030, the annual CO_2 emissions are expected to increase from around 190 million ton in 2012 to around 208 million ton in 2030 (reference scenario).
- The combined effect of larger vessels (EOS), implementation of EEDI and LNG as a fuel leads to a reduction of around 43 million ton CO_2 compared to the situation if the 2030 freight work would be transported with the 2012 vessel characteristics (size and efficiency). This corresponds to an efficiency increase of around 17% per ton nautical mile.
- The positive influence of EEDI and LNG as a fuel is still moderate in 2030 (7% CO_2 reduction in 2030). This will improve after 2030 due to the fact that a larger share of the vessel fleet will meet EEDI requirements. Also the share of LNG as a fuel is expected to increase and methane emissions of gas engines may be reduced, which will lead to a larger positive influence of LNG.

The following is concluded regarding the sensitivity analysis of the European maritime CO_2 emissions:

- The GDP growth rate has a dominant effect on annual CO_2 emissions. The 2030 European CO_2 emissions would increase from around 208 million ton to around 238 million ton annually, if the annual GDP growth rate would be 2.32% instead of 1.55%.
- A doubling of the EEDI influence would lead to a reduction of the CO_2 emissions of some 12 million ton annually.
- A doubling of the LNG fuel share (from around 10% to around 20%) would have a small effect and lead to an additional 1.5% CO_2 emissions reduction (3 million ton annually).
- Assuming a constant freight transport for crude oil between 2012 and 2030 (zero growth) leads to a CO_2 reduction of about 17 million ton annually (around 8%).

4. GHG abatement potential and cost curves [task 3]

4.1 Introduction

Ships emissions, their impact and solutions to reduce their emissions have been part of major studies such as: the *Second IMO GHG study 2009* (Buhaug et al., 2009); the *Technical support for European action to reducing GHG emissions from International Transport* (Faber et al., 2009); and the Quantify project which assessed the climate impact of global and European transport systems (Eyring et al., 2007). The combustion process in the engine(s) which converts fuel (generally hydrocarbons) into power and exhaust gases is the main source of these emissions. Of these exhaust gases: Carbon dioxide (CO_2) affects climate only, while Carbon monoxide (CO), Sulphur oxides (SOx), nitrogen oxides (NOx), methane (CH_4), black carbon (BC) and organic carbon (OC) affect climate and also have adverse health impacts (Lindstad and Sandaas, 2014). The emitted CO_2 is a function of the carbon content in the fuel. The emitted SOx are a function of the Sulphur content in the fuel. The emitted NOx is a function of fuel type, engine technology and the engine load relative to its rated power. The emitted BC, formed by incomplete combustion of fossil fuels, is a function of the engine load relative to its rated power. Scrubber technology or other after treatment of the exhaust gas is an effective means to reduce the emissions of SOx, NOx and BC. For vessels that use liquid natural gas (LNG) or gas in general as a fuel, leakage of unburnt methane CH_4 is a challenge, since methane is a greenhouse gas (GHG) which also damages crops and health when emitted at the ground. Furthermore, methane has a larger global warming potential of 30 compared to CO_2 over a 100-year period (IPCC, 2013).

In addition to the gases emitted from combustion there will be emitted greenhouse gases such as volatile organic compounds (VOC) when loading and discharging crude oil or oil products. VOC are chemicals that have a high vapour pressure at ordinary, room temperature, but compared to the greenhouse gas emissions from the combustion process these emissions are much smaller.

The main focus of this study is to identify options for reducing GHG emissions from shipping through reduced fuel consumption per freight unit or through fuels with lower or zero GHG equivalent impacts, which generally means that the other exhaust gas emissions will be reduced proportionally. In some cases however the reduction of CO_2 can be linked to the rise of other GHG emissions, such as methane. This effect is discussed for those emission reduction methods with this negative effect.

Previous studies have documented that it is possible to improve energy efficiency and reduce fuel cost and emissions in a cost effective manner, i.e. emissions can be cut with net cost savings (Buhaug et al., 2009; Faber et al., 2009; DNV 2010; IMAREST, 2011, Lindstad, 2013).

4.2 Marginal abatement costs curves

A marginal abatement cost curve (MACC) shows the cost-effectiveness of measures to reduce CO_2 emissions on the y-axis and the potential emission reductions on the x-axis. Marginal abatement cost (MAC) curves are a commonly used policy tool indicating emission abatement potential and associated abatement costs. Within the shipping at least four MAC curves have been previously published:

- The Second IMO GHG study (Buhaug et al., 2009)
- Technical Support for European action to reduce reducing Greenhouse Gas Emissions from international maritime transport (Faber et al., 2009)
- Pathway to Low Carbon shipping (DNV, 2010)
- Marginal Abatement Cost and Cost Effectiveness of Energy-Efficiency Measures (MEPC 61/INF 18)

Common for all of these studies are that they are based on shipping as it operated before the 2008 financial crisis, i.e. higher speeds and with less focus on environmental performance. In addition for some segment shipping, i.e. the Dry bulk the period prior to the 2008 crisis represented an all-time high market while the present represents an all-time low (Baltic Freight Index).

The main results and observations from the previous MAC curve studies will be compared with the MAC curves and main observations from this study in the concluding section of this report.

4.3 Emission Reduction Options

The CO_2 emission reduction options can be divided into two groups. Design measures which generally will be a part of new-building process or through retrofitting and operational measures which will be a function of vessel operations. To give an example, reducing emissions through slow speeding is an operational measure, while reducing emissions through building a slimmer hull is a design measure. Table 19 show the wide range of options for reduction of CO_2 emissions from ships by using known technology and practices which was identified by the *Second IMO GHG study 2009* (Buhaug et al., 2009).

Table 19: Potential CO_2 equivalent emission reductions (source: Buhaug et al. 2009)

Reduction option	CO_2 reduction per ton nautical mile	Combined	Combined
Design – new ships			
Concept, speed & capability	2% to 50%		
Hull and superstructure	2% to 20%		
Power and propulsion systems	5% to 15%	10% to 50%	
Low-carbon fuels	5% to 15%		
Renewable energy	1% to 10%		
Exhaust gas CO_2 reduction	0%		25% to 75%
Operation – all ships			
Fleet management, logistics & incentive	5% to 50%		
Voyage optimization	1% to 10%	10% to 50%	
Energy management	1% to 10%		

The following GHG abatement section consists of the following paragraphs:

- Design or Technical measures which will be a part of new-building process or through retrofitting;
- The operational measures which will be a function of vessel operations;
- The MAC curves per vessel type for three different vessels types based on a low, a medium and a high fuel price;
- The aggregated MAC curves for the whole fleet based on a low, a medium and a high oil price;
- The CO2 abatement potential for the different abatement scenarios; no regret, zero costs and maximum abatement, world-wide and for Europe.
- The 2020, 2025, and 2030 EU emissions
- Additional abatement options with alternative fuels (LNG, biofuel, H_2) and cold ironing.
- Compare the MAC curves from this study with the previous studies.

The focus of this study is on existing technologies which can be installed in ships in the very near future. In the description of the technical and operational measures also some of the options which have not been included have been described. To ease the readability, the included MAC options are addressed specifically in the paragraph headings.

4.4 Technical measures and changes in ship design

Speed, size and key parameters, such as beam, draught and length, have significant influence on the potential energy efficiency of a ship design. Specifying a ship with a standard lifetime of 25 to 30 years, and subsequently designing to that specification, is a highly complex task. The design specifications' impact on energy efficiency and emissions should not be underestimated (Brett et al., 2006; Winjnholst & Wergeland, 2009).

Traditionally seagoing vessels have been designed and optimized to operate at their boundary speeds based on hydrodynamic considerations. For any given hull form, the boundary speed can be defined as the speed area where the resistance coefficient goes from a nearly constant value at lower speeds and then starts to increase rapidly for higher speeds (Silverleaf and Dawson, 1966). For an average Panamax bulker with block coefficient in the 0.85–0.9 range (1.0 for a shoe box) the boundary speed area starts at 12–13 knots, with a gradual increase of resistance coefficient which goes against infinity for speed above 16–17 knots (Lindstad et al., 2014). As a simplification the form of the resistance coefficient can be compared to a quarter-pipe where the flat area in the bottom represents the lower speeds where the power required for propulsion is a function of the speed to the power of three. Common naval architecture practice has been to pick the achievable speed in the middle of the quarter-pipe curve where the power required for propulsion is a function of the speed to the power of four to five, commonly termed the maximum economic speed and installed the required power to achieve that speed (Lindstad et al., 2014). For Panamax bulkers this has typically resulted in design speeds of 14–14.5 knots and maximum speeds of up to 15 knots at calm water conditions (Lindstad et al., 2013). Comparing vessel types, more slender vessels designs such as large container carriers typically have block coefficients in the 0.6–0.65 range. This gives boundary speed areas starting at around 20 knots, and maximum economic speeds 23–26 knots range. See Larson and Raven, 2010 for a more extensive discussion of how hull resistance depends on speed and hull form.

When fuel goes into the ships main engine, 40% to 50% of the fuel energy is transformed to power delivered at the shaft. At the shaft we have additional loses before we get the propulsion thrust. This is illustrated in figure 9 which represents a well maintained cargo ship moving at about 15 knots in Beaufort 6 head weather condition. The bottom bar in this diagram represents the energy input to the main engine from the fuel. In this case, 43% of the fuel energy is converted into shaft power, while the remaining energy is lost in the exhaust or as heat losses. Due to further losses in the propeller and transmission, only 28% of the energy from the fuel that is fed to the main engine, generates propulsion thrust in this example. The rest of the energy ends up as heat, as exhaust, and as transmission and propeller losses.

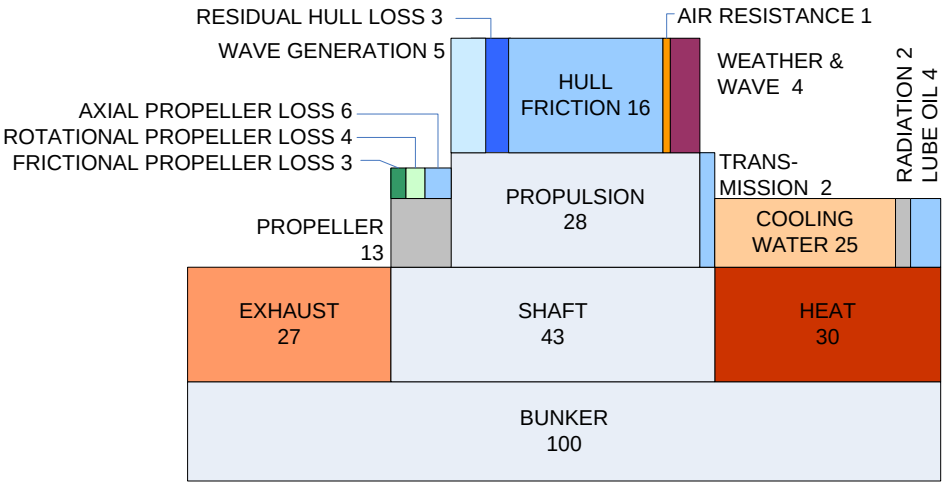


Figure 9: Use of propulsion energy on board a cargo ship, head sea, Beaufort 6

Higher fuel prices (i.e. from 250 - 300 USD per upwards compared to fuel cost around 100 USD per ton in the nineties) and increased environmental concerns have challenged this practice of maximizing cargo carrying ability and the practice of designing vessels to operate at speeds where the power required is a function of the speed to the power of four to five. For this reason, there has emerged a growing interest in the relationship between speed and emission reductions. The core insight is straight-forward: the power output required for propulsion is a function of the speed to the power of three to five and beyond; this simply implies that when a ship reduces its speed, the fuel consumption per freight work unit is reduced (Corbett et al., 2009; Psaraftis and Kontovas, 2010; Lindstad et al., 2011). Vessel size is another measure to reduce emissions, since the boundary speed increases with vessel length and hence enables larger vessels to operate at lower power consumption per freight unit than shorter ones at similar speeds (Stott and Wright, 2011; Kristensen and Lutzen, 2012). In addition to Carbon dioxide (CO_2) which is the main emission when fuel is burnt in combustion engines the exhaust gas contains sulfur oxides (SOx), nitrogen oxides (NOx) and particles (PM). This means that if shipping's fuel consumption is reduced through lower fuel consumption per freight unit transported all these emissions will be reduced proportionally.

4.4.1 *Slender Design*

Research on hull shapes and propeller design has focused on optimizing for still-water conditions, design cargo loads and design speed conditions (Faltinsen et al.,

1980); however, calm sea is rather the exception in shipping. Hirota et al. (2005) shows how the ship form might be optimized with respect to minimization of fuel consumption in waves, rather than in calm water. Van der Boom (2010) shows that if two vessels have equal beam measurements and equal length, the one with the longest bow section will experience less added resistance in waves compared to the one with a shorter bow section. Calculation of added resistance in waves has also been studied by several authors (Lloyd, 1988; Steen and Faltinsen, 1998; Arribas, 2007; Guo and Steen, 2010). Lindstad et al. (2013a); Lindstad 2013a; Lindstad et al 2014; Lindstad and Eskeland (2015) has assessed cost and emissions as a function of alternative bulk and tank vessel designs and found that with present fuel cost, emissions can be reduced significantly, at a net saving by designing and building more slender vessels.

The additional capital expense of an optimized hull shape where main measurements, i.e. length, beam and draft, has been altered to enable more slender designs, while maintaining constant cargo carrying capacity is estimated to be around 10% of the new-build vessel cost. The energy and emission reduction potential based on Lindstad et al (2013); Lindstad (2013); Lindstad (2014); Lindstad and Eskeland (2015) goes from 10% for container vessels up to 30% for the dry bulkers.

4.4.2 *Propeller Upgrade*

The ideal efficiency of any size propeller is that of an actuator disc in an ideal fluid. In practice high propeller efficiency can be obtained with a large propeller rotating at low speed. Ideally, the number of blades should be minimized, to reduce blade area and frictional resistance. Typical design restrictions are limitations on diameter, cavitation and loading. Despite these restrictions there is a general potential for improving propeller efficiency and projects like Streamline (2010) and similar has tried to identify an increase in efficiency of at least 15% compared to the current state of the art.

The additional capital expense for an optimized propeller including good hydrodynamic design of the aft section is a function of engine size and vessel type. The energy and emission reduction potential has been estimated to be around 5% for all the investigated vessel types.

4.4.3 *Ballast Water Reductions*

Since the introduction of steel-hulled vessels from 1850 onwards, water has been used as ballast to stabilize vessels at sea. This practice reduces stress on the hull, provides transverse stability, improves propulsion and maneuverability, and compensates for weight changes in various cargo load levels and due to fuel and water consumption. In total, Shipping transfers approximately 3 to 5 billion ton of ballast water internationally each year (Godey et al. 2014). This ballast water transferred between different ports is a serious environmental problem since there are many marine species that are carried in ship’s ballast water which are small enough to pass through a ships intake at ports and when discharged, lead to severe ecological problems when the ballast water is discharged in another part of the world. The ballast treatment legislation by IMO which now has been ratified will reduce this problem significantly, however if ballast water usage can be reduced or eliminated, it is possible to save fuel usage per voyage and fuel usage for pumping and treating ballast. Several concepts have been studied and one is the E/S Orcelle by Wallenius Wilhelmsen asa, which represents a vision for zero-emission car

carrying ocean going vessel. The idea combines fuel cells, wind, solar and wave power to propel the vessel, that will need no oil or ballast water. Another is a ship which has been developed in which ballast water exchange and treatment is avoided by providing flow-through longitudinal pipes in the double bottom instead of conventional ballast tank. In a search to eliminate non-native creatures to sneak into the Great Lakes from overseas, the University of Michigan jointly with Japan's National Maritime Investigation Institute are developing ballast-free ships by means of longitudinal ducts along the hull which, as a secondary benefit seems to produce significant fuel savings due to a better flow of water on the propeller. The design appears to provide a significant savings – possibly as much as 7.3% in the power needed to propel the ship. For a 650-foot bulk carrier hauling 32,000 metric tons of cargo from the Great Lakes to Europe and back, that translates into a roundtrip fuel savings of roughly $150,000.

The additional capital expense for vessels which requires less ballast, but not eliminates it, is estimated to be in the range of 2 – 5% of the hull cost. The energy and emission reduction potential is estimated to be 2.5%, which is less than for the more innovative concepts as described above. However more research is needed within this field to fully develop such concepts which can be built for a moderate additional cost compared to standard designs.

4.4.4 *Fuel Cells*

Emissions of CO_2 can be cut by switching to fuels with lower total emissions through fuel cycle including production, refining and distribution (Buhaug et al., 2009). Bengtsson et al. (2012) derive a conclusion that the biofuels are one possible measure to decrease the global warming impact from shipping, but that it can be to the expense of greater environmental impact for other impact categories such as eutrophication and energy to produce biofuels. Liquefied natural gas (LNG) has higher hydrogen to carbon ratio compared to diesel and Heavy Fuel Oil (HFO), which results in lower CO_2 emissions (Stenersen and Nilsen, 2010). Hydrogen is another interesting fuel since the combustion outputs of only water and energy, and hence no CO_2. Hydrogen can also be used in fuel cells. The FCSHIP-project has investigated the use fuel cells on board ships, and the offshore supply vessel Viking Lady has a fuel cell installed to produce part of the energy that otherwise would be produced by the auxiliary engines (Biello, 2009).

Fuel cells and cold ironing are considered an abatement option in the category of renewable fuels and can be used to deliver the auxiliary power supply of vessels. Fuel cells might replace the traditional auxiliary engines partly or wholly and might give an efficiency improvement of up to 20%. In relation with the overall energy consumption of the vessel, this improvement results in a reduced energy demand of 1- 3%, depending on the size of the auxiliary power supply of the vessel. The additional capex are found by taking the price difference with the cost of the regular auxiliary power.

The capex cost for cold ironing is around 100.000 EUR. This is a fixed additional cost for all the vessels that covers minor changes in the ship design and in the education of the on board staff to learn how to operate with the on-shore power supply. However even if the ambition for the renewable energy in the EU is taken into account - 45% in 2030 (EREC, 2014) the GHG reduction achievable by cold ironing is marginal. But cold ironing is an efficient way of reducing locale harmful

pollutions such as nitrogen oxides (NOx), methane (CH4), black carbon (BC) and particle matters (PM) in port.

4.4.5 *Wind power*

Interest has re-emerged in wind assisted ships. These are typically intended to operate in wind-assist or motor sailing mode in which the speed is maintained irrespective of wind speed and direction. Wind propulsion systems can be divided into three groups. The first is modern implementation of conventional soft sail rigs. One example is the Dynarig which offers high aerodynamic efficiency with minimal crew based on concepts proven on mega yachts (Perkins et al., 2004). The second group is kite propulsion, such as delivered by Skysails which have been studied by Dadd et al. (2011) and tested on the 140 meter long cargo vessel Beluga Sky-Sails in the Wintecc project (2007). The third group utilizes the Flettner rotor concept which requires little space on the deck and performs well in side wind condition. Wind conditions differ between regions, so that wind power is more attractive in certain regions and routes than in others. In a study carried out by Clauss et al. (2007), three different types of sails were modelled on two types of ships on three different routes using actual weather data. The study indicates that the potential for sail energy was better in the North Atlantic and North Pacific than in the South Pacific. Fuel savings were typically about 20% for a vessel speed of 10 knots.

Capex of wind power has been estimated by taking an investment cost of 4000 EUR/kW, which is in the range mentioned by (Hekkenberg, 2013).The annual fuel and emission reduction potential are in the range of 5 to 10% based on published studies such as Traut et al. (2014). And in this study we have used 5% for the vessel types which wind power is applicable. Wind energy by means of kites or Flettner rotors is not an abatement option for the following vessels: general cargo, container, reefer, chemicals, LNG&LPG and RoPax.

4.4.6 *Solar energy*

Solar cell technology is improving rapidly and might soon be cost competitive with other emission reductions technologies. One example is Nissan’s 1380 capacity car carrier The Nichioh Maru. The ship's deck is covered by 281 solar panels for powering the LED lights through the hold and crew quarters, eliminating the need for a diesel-fuelled generator. Compared to a conventional car carrier of its size, the Nichioh Maru will save 1,400 tons of fuel and prevent the emission of 4,200 tons of CO_2 each year (Westlake, 2012). The emission reduction potential of installed solar cells on board ships could be addressed, by considering the maximum install deck area, as well as the operational profile and the geographical area where these vessels operate.

In this study the GHG reduction potential of solar cells is found by assuming that 1% of the auxiliary power is generated by solar cells. This corresponds to realistic surface areas of solar installation, when considering that 1 square meter of solar panels corresponds to 200 W. The CAPEX of solar cells is taken to be 4000 EUR per kW. This is within the range of the figures mentioned by (Hekkenberg, 2013), (Glykas, Papaioannou, & Perrisakis, 2010) and by (Trapani, Millar, & Smith, 2012).

4.4.7 *Waste heat recovery*

When fuel goes into the ships main engine, 40% to 50% of the fuel energy is transformed to power delivered at the shaft, while the remaining energy is lost as exhaust gas and through heat exchange with air and cooling water as illustrated in

figure 2. Part of this energy can be recovered from exhaust gas by using steam turbines. The power that is recovered can then be used to drive auxiliary machines or to assist the main engine. This allows for up to 12% savings on primary fuel and hence CO_2 (Emec, 2010). In tests, emissions were reduced up to 14% (Green ship of the future, 2012).

In this study, a GHG savings potential of less than 8% is considered, this is in range with the figures mentioned in the literature (e.g. (OECD, ITF, 2009) (Hekkenberg, 2013)). Waste heat recovery is not an option for oil and chemical tankers since these vessels use the waste heat for other purposes. The CAPEX of a waste heat recovery system is approximated by taking an additional 300 EUR/kW for the main engine. This is the lowest value mentioned by (Hekkenberg, 2013) and would cover the cost of an extra Rankine cycle system on board.

4.4.8 *Hybridization*

Power solutions for seagoing vessels are generally designed to ensure that vessels have the required power to be seaworthy in rough weather and to achieve their design calm water speed at 75% to 85% of installed power (Lindstad, 2013). Historically, fuel cost was small compared to the other costs of the vessel. These other costs are mostly fixed, with the result that operating at medium to high power which gives the lowest fuel consumption and emissions per produced kWh, was the best strategy to minimize cost and maximize profit. Present prices of fuel have challenged design speed operations and the average speed at sea has been reduced, i.e. slow steaming. For the engine(s) reducing speeds implies that power is reduced and operating at 15 – 40% of installed power has now become a general practice in shipping. When engines operate at low power, fuel consumption per kWh produced increases. For the cost of the operation, this increase in specific fuel consumption and hence CO_2 per kWh produced at lower loads makes a small impact compared to the total cost of the operation, while for emissions low loads implies that emissions of exhaust gases such as nitrogen oxides (NOx) and aerosols such as black carbon (BC) increases rapidly due to less favorable combustion conditions. Hybrid technologies in one option for offsetting the disadvantages of reduced power outtakes. In this context hybrid means engines of different sizes, battery storage of energy to take peak power requirements, and power management systems with a more balanced focus on reducing emissions and energy consumption while maintaining a high safety standard.

The additional capital expense is in the range of 25% of the price of the main engine. This allows for a more complex power generation system in terms of number of elements. It is assumed that the maximum savings potential of hybridization is 5% for most vessel categories. For RoPax vessels a maximum saving potential of 10% is assumed. This is within the range mentioned by DNV GL (2014) and Lindstad and Sandaas (2014).

4.4.9 *Efficient lighting*

In addition to the options described above fuel consumption can in addition be reduced by technical measures such as: improvements on the engine, more advanced control systems for auxiliary units, electric lightning which use less electricity (Buhaug et al 2009; Faber et al 2009; DNV, 2010; Faber at al. 2009; Faber at al. 2011; AEA-Ricardo, 2013).

Most of these options have been utilized, but there is still a potential for saving energy through efficient lightning. The saving potential has been estimated to be 1.5% in the overall energy consumption. For RoPax vessels 3% saving potential has been estimated. The investment cost has been estimated based on the vessel size and category in a range of 50,000 to 200,000 EUR.

4.5 Operational measures for GHG abatement

4.5.1 *Slow Steaming*

Perhaps the most obvious way to reduce GHG emissions is to reduce the sailing speed of vessels. The relationship between speed and emissions has been discussed by many authors such as (Corbett et al., 2009; Seas at Risk and CE Delft, 2010; Psaraftis and Kontovas, 2010, Lindstad et al, 2011; Lindstad 2013). The background for the focus on speed reductions is that ships have typically been built to operate at their boundary speeds based on hydrodynamic considerations with design loads at still water conditions. For any given hull form, the boundary speed can be defined as the speed area where the resistance coefficient goes from a nearly constant value at lower speeds and then starts to increase rapidly for higher speeds (Silverleaf and Dawson, 1966). High prices of fuel and increased environmental concerns have challenged this practice and for this reason, there has emerged a growing interest in the relationship between speed and emission. The core insight is straight-forward: the power output required for propulsion is a function of the speed to the power of three to five and beyond; this simply implies that when a ship reduces its speed, the fuel consumption per freight work unit is reduced. See table 20 where average power are estimated on design speed and average speed published in The Third IMO GHG study (Smith et al. 2014) illustrates current operational speeds and power levels per vessel type.

The additional capital expense for slow steaming is marginal, i.e. unless the average power is reduced bellow 15 – 20%. For the energy and emission reduction potential the table shows that most of the slow steaming benefits have been achieved, however there are some additional potentials. This potential is however limited by the fact that when speed is further reduced, the power for auxiliary, waves and wind and currents exceeds the pure still water propulsion power. This means that when speed is reduced bellow the speed which gives the lowest emissions per ton nm emissions will increase per ton nm (Lindstad et al 2011; Lindstad et al 2013a). For smaller vessels this speed will be in the 6 – 8 knot range while for larger vessels it will be in the 8 – 10 knot range and for vessels which carries frozen or fridge goods, i.e. reefer, container and Ro-Ro it might be in the 12 – 15 knot range due to the significant amounts of electricity which is needed (Lindstad, 2013). Based on this, we have calculated the additional fuel and emission reductions to go from 0% for RoPax and Gas carriers up to 17 – 18% for the dry bulkers and crude oil carriers.

Table 20: Current operational speeds and power levels per vessel type

Vessel type	Average vessel size in dwt 2007	Average vessel size in dwt 2012	Design Speed 2012	Average Speed 2012	Average Power
	ton	ton	knots	knots	
Dry Bulk	52 500	68 600	14.8	11.5	40%
General Cargo	4 600	5 300	12.5	9.3	35%
Container	34 200	41 600	21.3	14.6	27%
Reefer	5 400	5 700	16.2	13.4	48%
RoRo	7 200	7 600	16.3	15.0	66%
OilTanker-mainly crude > 80' dwt	176 500	183 500	15.7	11.9	37%
OilTankers-mainly product < 80'dwt	9 800	13 300	12.4	9.4	37%
Chemicals	15 800	18 000	13.6	11.1	46%
LNG & LPG	22 800	27 600	15.6	12.9	48%
RoPax	1 400	1 600	16.6	10.7	23%
Totals Cargo Vessels	22 500	30 800	14.6	11.1	37%

4.5.2 *Advanced route planning*

Voyage optimization concerns to find the shortest feasible route between port of departure and port of arrival, and then weather, current and wave data in combination with the vessel characteristic can be used to find the deviations and speed combinations which minimize resistance and fuel consumption for the given freight market. Such selection of routes between ports to find the optimum voyage, when current and weather conditions are taken into account, is often referred to as weather routing. McCord et al. (1999) concluded in a case study that 11% fuel savings could be achieved for a 16-knot vessel by utilizing ocean currents while Lo et al. (1991) estimated a significant reduction in world fleet fuel consumption by utilizing ocean currents. Lindstad et al (2013a) has assessed profit, cost and emissions as a function of speed, sea conditions and freight market and found that power models in combination with weather data enables deep sea voyage routings which reduces cost and emissions per voyage with 11 – 19% in rough weather periods. These figures are of the same magnitudes as indicated by Strom Tejsen et al. (1975).

The savings potential within a range of up to 10%, matches with the figures mentioned by (OECD, ITF, 2009) and (Watson, 1998). For this study 10% saving is used for deep sea ships, while 5% is used for short sea ships. For the latter category there are much fewer options to save energy, since for example weather routing is not a real option. The investment cost per vessel has been estimated to be 50,000 EUR for short sea and 100,000 EUR for deep sea ships.

4.5.3 *Profit Sharing*

Ship scheduling and routing concerns the optimal assignment of available cargoes to a set of ships in the fleet, where “optimal” signifies either lifting (transporting) all cargoes while minimizing costs or maximizing profit by only assigning profitable cargoes. Several authors have in different contexts incorporated speed optimization into the routing decisions (Bausch et al., 1998; Fagerholt, 2001; Alvarez, 2009; Fagerholt et al., 2010; Norstad et al., 2010).

These studies show that the fuel savings from including speed optimization can be large. But, berthing policies used at ports often admit vessels on a first-come, first-served basis which is an argument for ensuring that speed optimization is synchronized with port planning (Alvarez et al., 2010).

Both BIMCO and INTERTANKO has introduced contracts which enables the ship-owner and their customer to share the cost savings, which can be achieved by speed optimization and virtual arrivals instead of the traditional first come, first serve within the Lay-Can spot and where demurrage is one of the rewards for the ship-owner. Profit sharing is only an option for vessel categories which have flexibility regarding planning and logistics. It has been assumed that this is the case in general for general cargo, dry bulk and the tanker vessel categories. For those a potential GHG reduction of 2% is assumed.

4.6 The Reference Vessels

In this study we have chosen to use the expected average vessels size in 2030 per vessel type, i.e. as specified in Table 11, section 3.3.2. For each of the vessel types (apart for the LNG&LPG and RoPax) reference vessels have been identified. The reference vessels are presented in the Appendix B. These reference vessels are all built during the last 5 years, or have recently been launched and are to be taken in service soon. See table 21 for an overview of average vessel size in 2030 and IMO numbers for reference vessels.

Table 21: Average vessel size in 2030 and IMO numbers for reference vessels

Vessel type	DWT	IMO	IMO	IMO
Dry bulk	98000	9599078	9641376	9599200
General cargo	7000	9618721	9694701	9561007
Container	77000	9679555	9475648	9660011
Reefer	7000			
Roro and vehicle	11000	9609964	9668506	9687306
Oil tanker +80 dwt crude	189000	9452880	9607423	9461776
Oil tanker -80 dwt product	12000	9394076	9706944	9621663
Chemicals	29000	9622069	9617650	9733674
LNG & LPG	46000			
RoPax	2300			

4.7 Quantification of Energy savings and cost per abatement measure

An overview of the energy and GHG saving potential of the abatement measures as described in the previous sections is presented in Table 22. The CAPEX investment costs are presented in table 23. All numbers are in Euro's. In case they were based on dollar values an exchange rate of 1.2 USD per Euro is used.

Table 22: Overview of CO_2 saving potential (%) for different abatement measures compared to 2030 reference.

CO2 saving potential %	Dry Bulk	General Cargo	Container 4000 TEU	Reefer	RoRo & vehicle	OilTanker-mainly crude > 80' dwt	OilTankers-mainly product < 80'dwt	Chemicals	LNG & LPG tanker	RoPax
Profit sharing & v.a.	2	2	n/a	n/a	n/a	2	2	n/a	2	n/a
Advanced route planning	10	5	5	5	5	10	10	5	5	n/a
Slow steaming	17	11	2	2	16	18	12	17	n/a	n/a
Efficient lighting	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**1.5**	**3.0**
Optimised propeller	5	5	5	5	5	5	5	5	5	5
Slender hull	30	20	10	10	15	25	20	20	10	10
Ballast water reduction	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**	**2.5**
Hybridisation	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**5**	**10**
Waste heat recovery	3.5	3.5	3.5	3.5	3.5	n/a	n/a	n/a	3.5	3.5
Solar cells	0.2	n/a	n/a	n/a	0.2	0.2	0.2	0.2	0.2	n/a
Wind power	5	n/a	n/a	n/a	5	5	5	n/a	n/a	n/a
LNG as fuel	8	8	8	8	8	8	8	8	8	8
Biofuels (10% Blend / 90% Diesel)	6	6	6	6	6	6	6	6	6	6
H2 fuel cell for aux power during sailing	3	3	5	4	2	4	3	3	3	4
H2 fuel cell for aux power during sailing and in port	7	7	9	11	5	7	8	7	7	9
Cold ironing	4	5	5	7	3	4	5	5	3	6

Table 23: Investment costs for different abatement measures (EUR)

Additional investment costs (euro)	Dry Bulk	General Cargo	Container 4000 TEU	Reefer	RoRo & vehicle	OilTanker-mainly crude > 80' dwt	OilTankers-mainly product < 80'dwt	Chemicals	LNG & LPG	RoPax
Profit sharing & v.a.	0	0	n/a	n/a	n/a	0	0	n/a	0	n/a
Advanced route planning	100,000	50,000	100,000	50,000	50,000	100,000	50,000	50,000	50,000	n/a
Slow steaming	0	0	0	0	0	0	0	0	0	0
Efficient lighting	100,000	50,000	200,000	100,000	100,000	200,000	50,000	100,000	100,000	200,000
Optimised propeller	575,000	205,000	1,137,500	250,000	290,000	937,500	217,500	350,000	445,000	380,750
Slender hull	2,960,000	1,140,000	2,540,000	1,140,000	1,220,000	4,780,000	1,240,000	1,580,000	1,920,000	1,046,000
Ballast water reduction	715,000	265,000	1,128,750	292,250	407,500	1,613,750	552,500	598,500	617,000	1,081,250
Hybridisation	1,720,000	1,112,500	4,180,000	1,288,750	1,337,500	2,260,000	1,090,000	1,306,000	1,432,000	1,675,000
Waste heat recovery	2,200,000	1,250,000	6,300,000	1,550,000	1,750,000	n/a	n/a	n/a	2,200,000	2,500,000
Solar cells	96,000	n/a	n/a	n/a	60,000	168,000	20,000	68,000	96,000	n/a
Wind power	1,694,800	n/a	n/a	n/a	1,595,351	2,190,816	1,139,738	n/a	n/a	n/a
LNG engine and tank	6,600,000	3,750,000	18,900,000	4,650,000	5,250,000	9,300,000	3,750,000	5,550,000	6,600,000	7,500,000
Biofuel blend	0	0	0	0	0	0	0	0	0	0
H2 fuel cell for aux power	13,200,000	2,750,000	58,300,000	12,100,000	8,250,000	23,100,000	2,750,000	9,350,000	13,200,000	16,500,000
Cold ironing	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000	100,000

4.7.1 *Stakeholders feedback*

Feedback on individual abatement measures was obtained from three stakeholders (three shipping companies). This primarily concerned general cargo and container vessels.
In most cases they agreed with the used assumptions (table 22 and 23), although mentioned differences are:

- Lower potential for hull optimization/ slender hull: less than 10% instead of 20% (for this study rather extensive hull adaptations are considered possible).
- Higher potential for slow steaming: 25% instead of 11% for general cargo. However in this study most of the slow steaming benefit is already included in the 2012 reference which explains the lower potential as further abatement measure. Refer to section 4.5.1.
- Waste heat recovery was considered more cost effective (container vessel).
- Lower investment costs for advanced route planning (15,000 to 25,000 instead of 50,000 EUR, although in one case also a yearly contribution was given).
- Lower investment costs for efficient lightning (around 25,000 instead of 50,000 EUR).

4.8 The Marginal Abatement Cost (MAC) curves

A marginal abatement cost curve (MACC) shows the cost-effectiveness of measures to reduce CO_2 emissions on the y-axis and the potential emission reductions on the x-axis. The MAC – curve plots the maximum achievable reductions against estimated cost-effectiveness. Assuming that the most cost-effective measures for reduction of emissions are implemented first, the subsequent options will be more expensive and less effective. MAC - curves always considers the cost of reducing the emissions by the next tonne of CO_2, given the reduction that has been achieved by the options that have already been implemented.

In this section, the marginal abatement cost curves for the different reference vessels are presented and discussed. For the purpose of this study, we focussed on the most important abatement options.

These are in alphabetic order:

- Advanced Route Planning
- Ballast water reduction
- Efficient Lightning
- Fuel Cells
- Hybridization
- Profit Sharing
- Propeller Upgrade
- Slender Design
- Slow Steaming
- Solar Energy
- Wind Power
- Waste Heat Recovery

We could in addition have included hull monitoring, anti-fouling and trim draft. However, in general ship owners have already implemented these measures.
In figure 10 to 19 the marginal abatement cost curves (MACC) of different reference vessels are given (as defined in the ANNEX A ‘Reference vessels’).

The savings potentials, CAPEX and OPEX, are taken as discussed in the previous section. From the figures, it is seen that several abatement options are always cost-effective independent of the vessel category, such as profit sharing, trim/draught and weather routing. Others are always costly in terms of ΔTCO, such as waste heat recovery, energy efficient light systems and additional hull monitoring.

There is one page per vessel type and three MAC-curves on each page. The first (at the top) shows the Mac-curve with a fuel price of 250 €/ton. The second (in the middle) shows the MAC-curve with a fuel price of 500 €/ton. The third (at the bottom) shows the MAC-curve with a fuel price of 1000 €/ton. The highest of these prices reflects the peak cost of distillate, i.e. Marine Gas Oil and Marine Diesel Oil which we experienced in 2012 – 2014. The middle, i.e. 500 €/ton reflects the low end of the Heavy Fuel Oil prices we saw in 2012 – 2014, while the 250 €/ton reflects early 2015 prices of Heavy Fuel Oil. In a historic setting all these prices are high compared to the +-100 € per ton in the end of the nineties and early 2000.

The potential GHG reductions through use of LNG or biofuels have not been included in the MAC-curves, because LNG is already included in the reference scenario, while for biofuels only limited amounts of fuel are foreseen to be available. But similar MACs also apply to vessels sailing on LNG and regarding the cost-benefit part also to vessels sailing on biofuels, if the prices of those fuels are similar. Since the MACCs are made with three fuel prices (250, 500 and 1000 EUR/ton diesel equivalent), LNG and biofuel would likely also fall in this range. For LNG the CO_2 savings per measure will be 5-10% lower, because that advantage is already obtained by applying LNG. With similar reasoning, if a ship would run on biofuel, the additional GHG saving of abatement measures is strongly reduced dependent on the type of biofuel and the definition which is applied (whether it would regard a Well to Propeller or a Tank to Propeller assessment). However, the cost benefit part for the ship owner, would still work in the same way as with conventional fuel. So a cost-effective abatement measure with conventional fuel will also be cost-effective with LNG and biofuels (provided fuel prices are similar or higher).

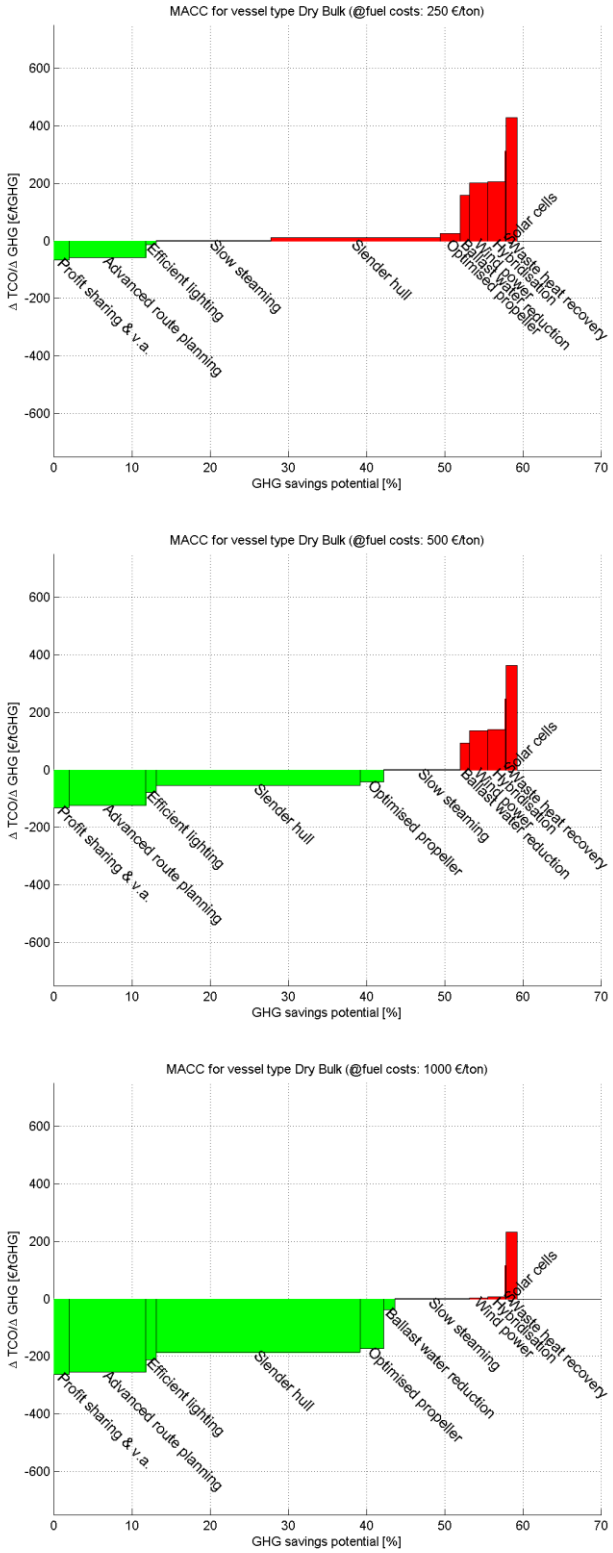


Figure 10: MACC for vessel type Dry Bulk (@fuel costs of 250 – 500 – 1000 €/ton)

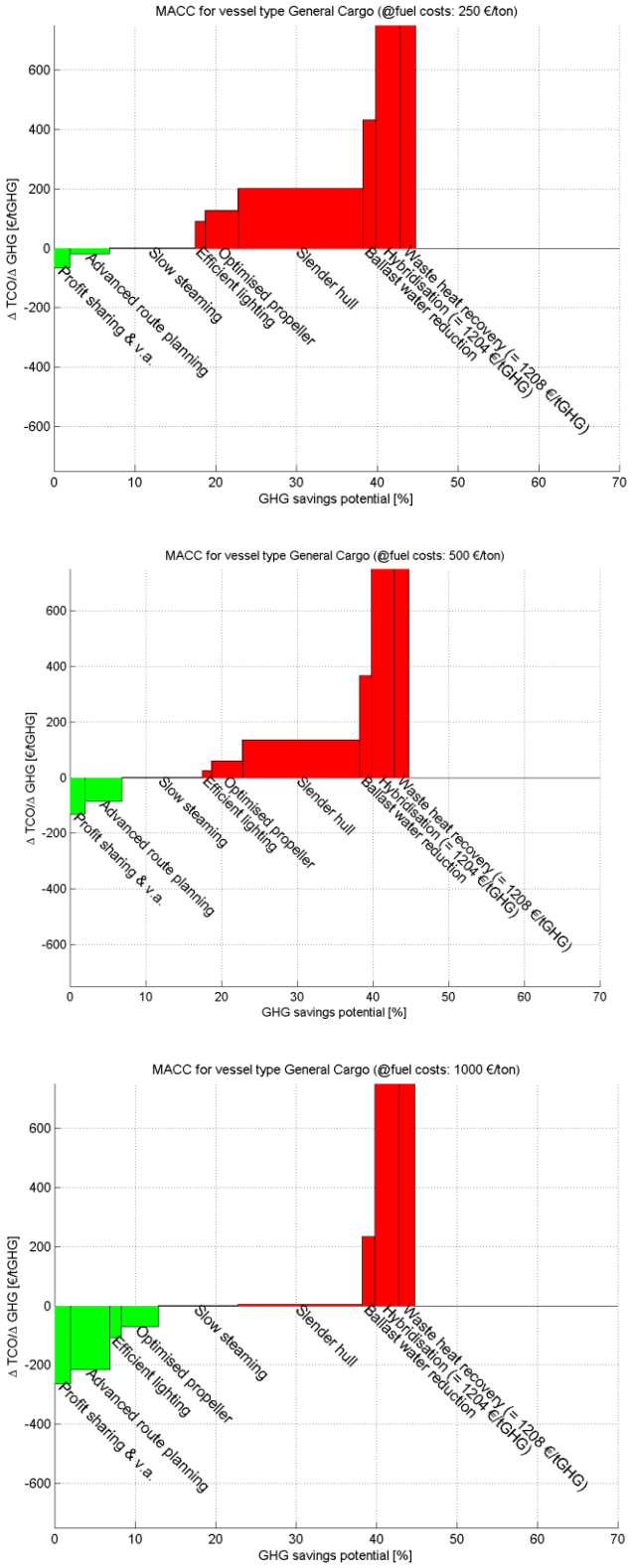


Figure 11: MACC for vessel type General Cargo (fuel costs: 250 – 500 – 1000 €/ton)

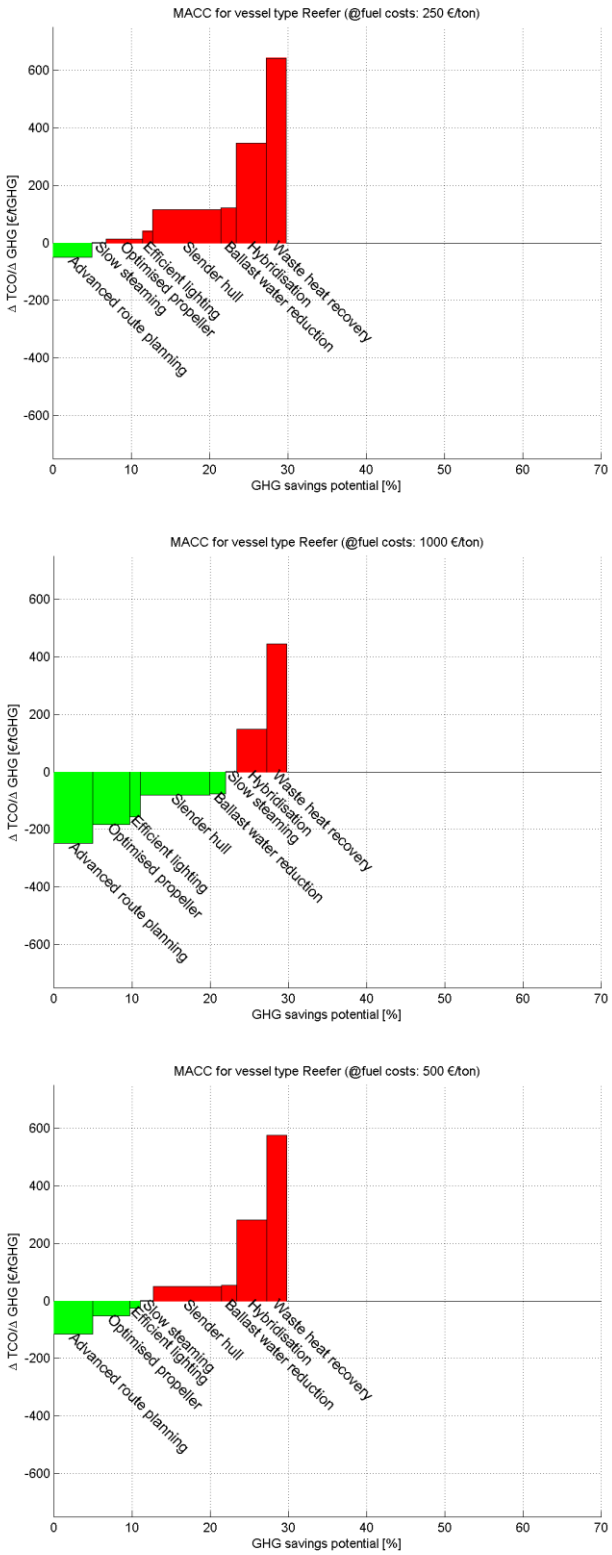


Figure 12: MACC for vessel type Reefer (fuel costs: 250 – 500 – 1000 €/ton)

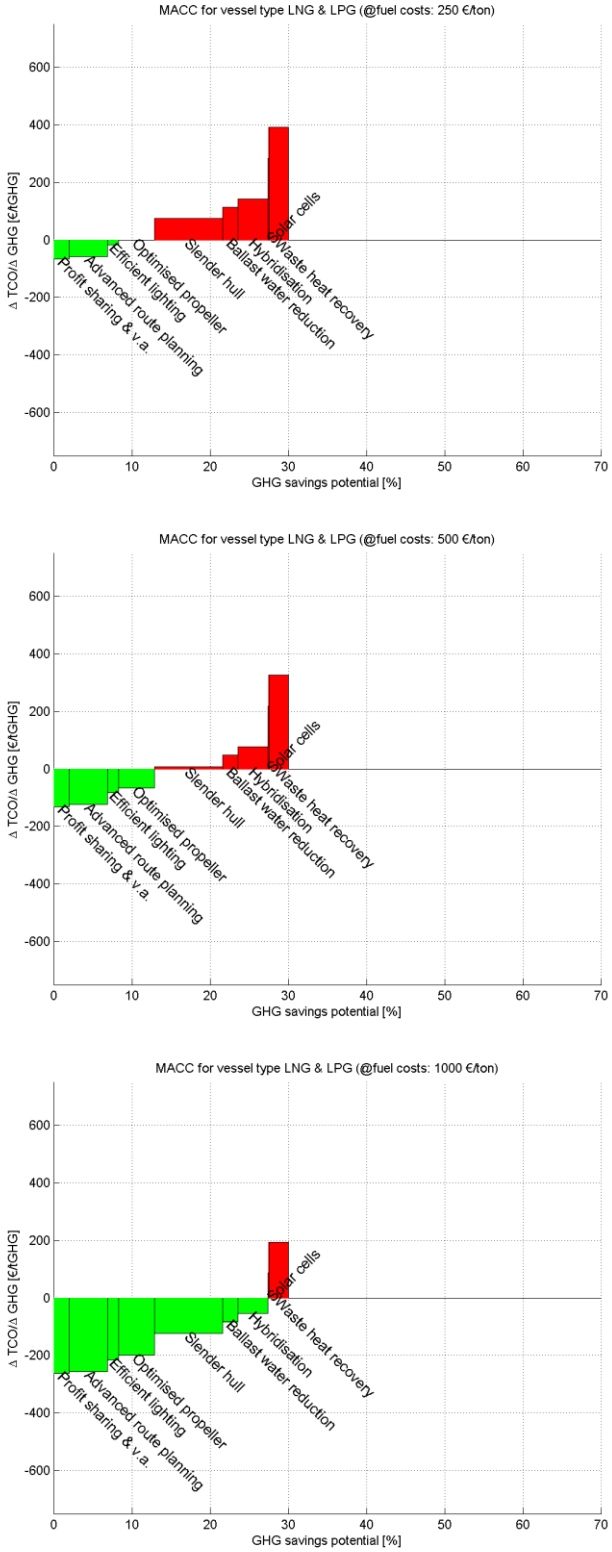


Figure 13: MACC for vessel type LNG & LPG carrier (fuel costs: 250 – 500 – 1000 €/ton)

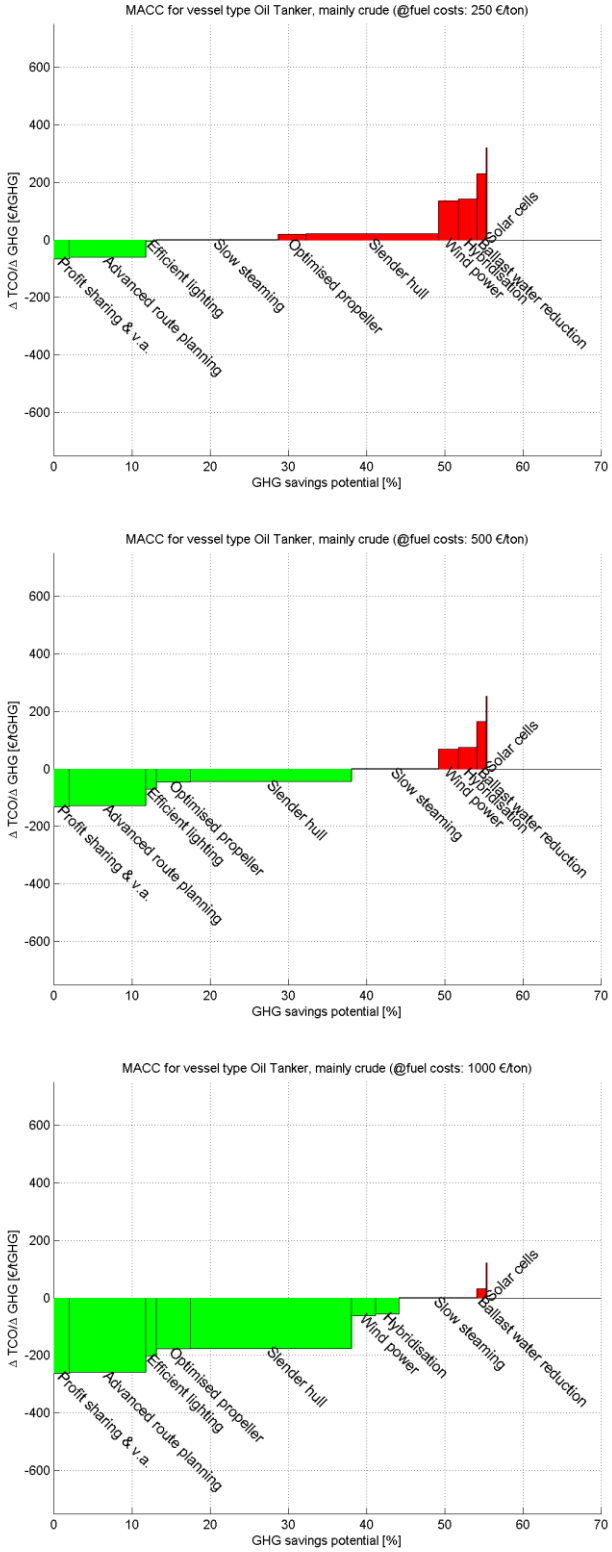


Figure 14: MACC for vessel type Oil Tanker, mainly crude (fuel costs: 250 – 500 – 1000 €/ton)

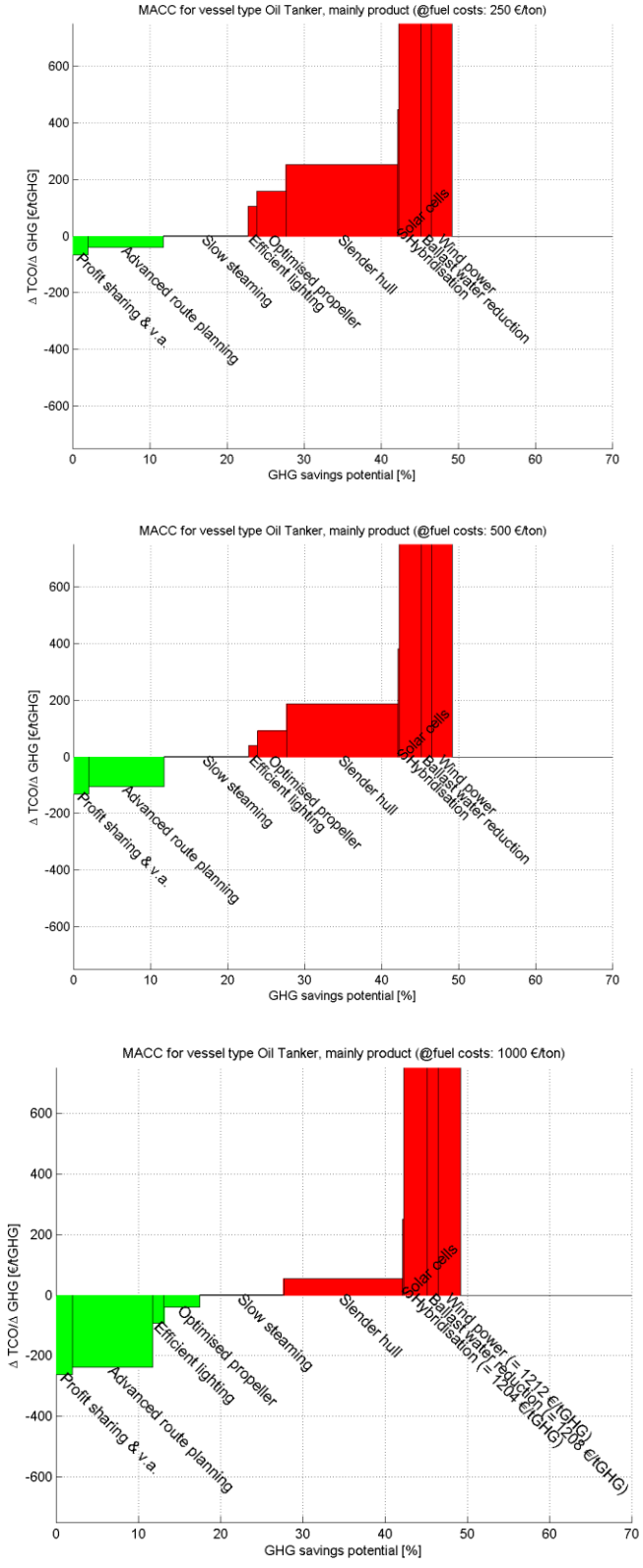


Figure 15: MACC for vessel type Oil Tanker, mainly product (fuel costs: 250 – 500 – 1000 €/ton)

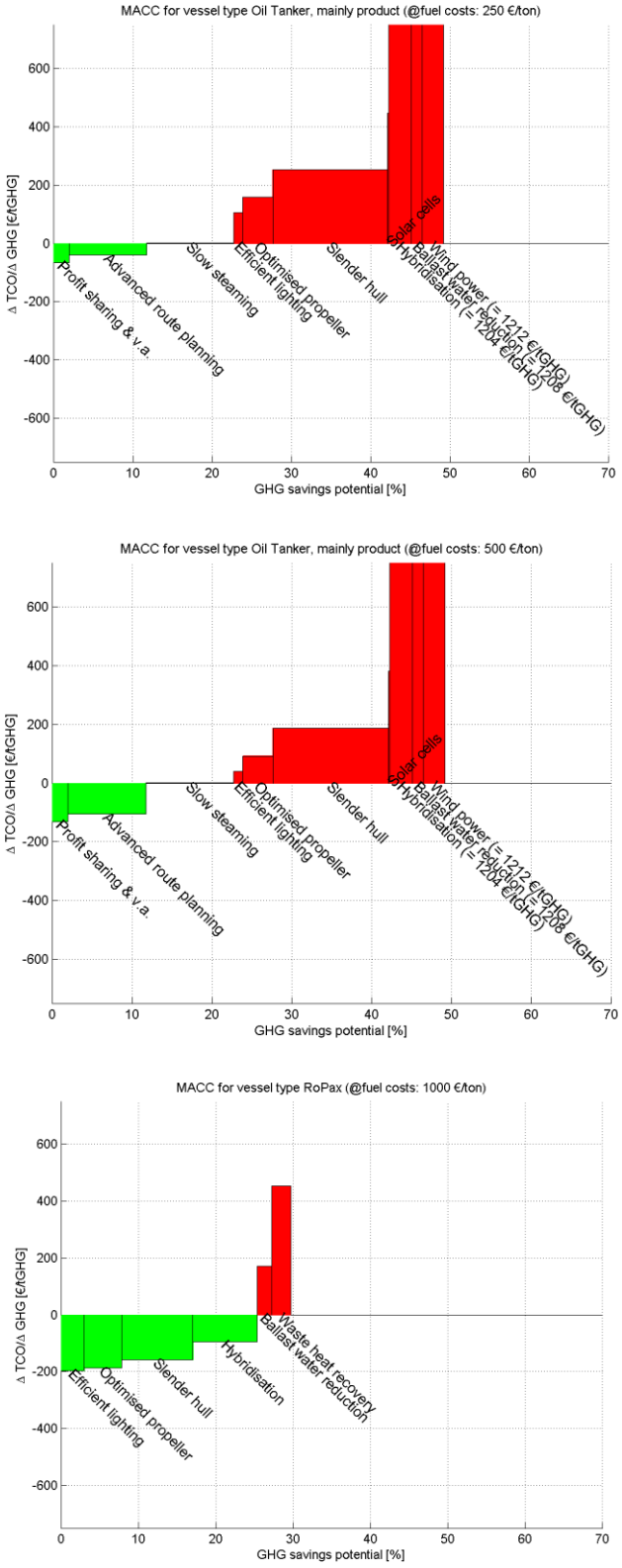


Figure 16: MACC for vessel type RoPax (@fuel costs of 250 – 500 – 1000 €/ton)

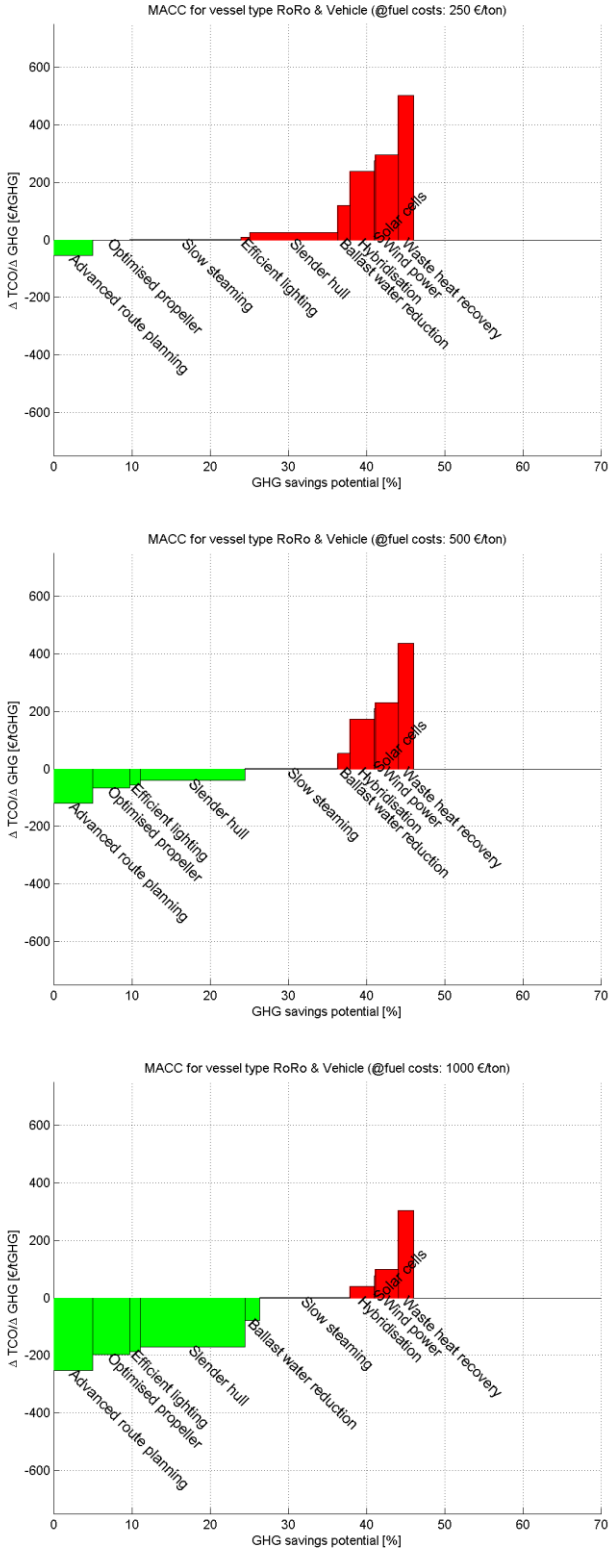


Figure 17: MACC for vessel type Ro-Ro & Vehicle (@fuel costs of 250 – 500 – 1000 €/ton)

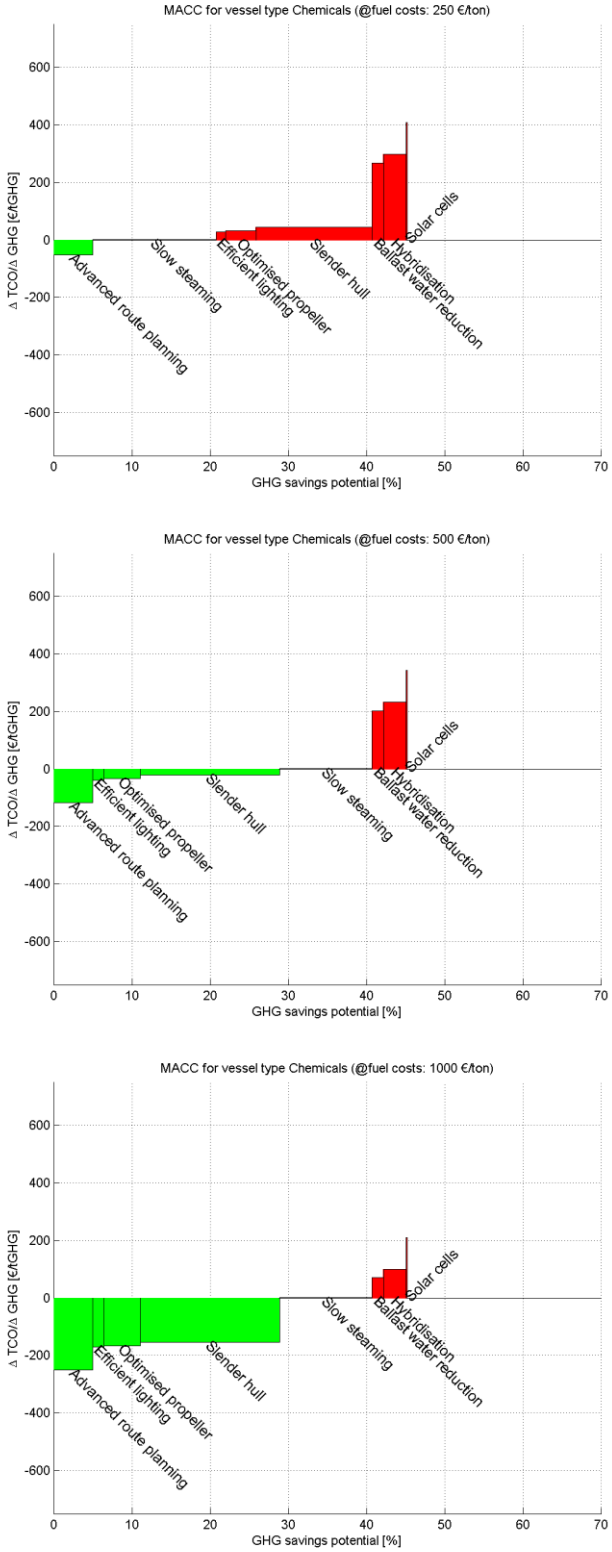


Figure 18: MACC for vessel type Chemicals (@fuel costs of 250 – 500 – 1000 €/ton)

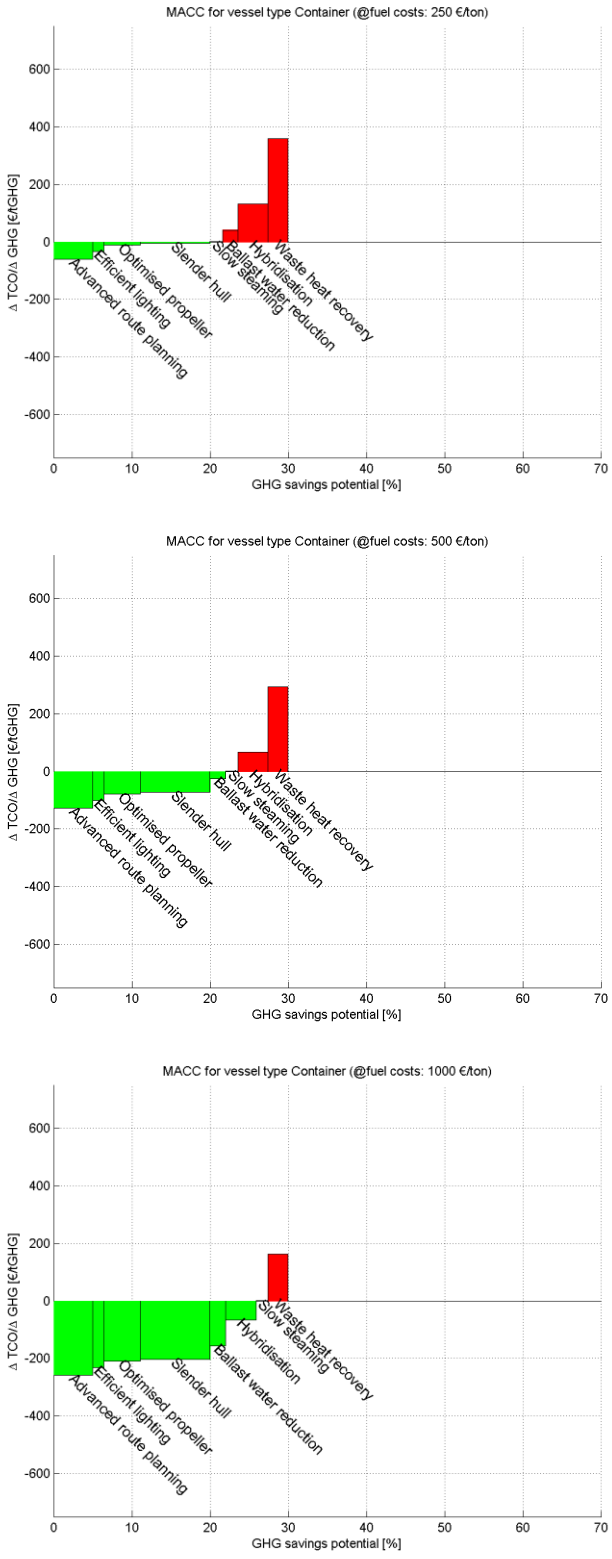


Figure 19: MACC for vessel type Container (@fuel costs of 250 – 500 – 1000 €/ton)

4.9 CO_2 abatement scenarios

The aim of this analysis is to determine the overall GHG reduction potential for 2030. Based on the marginal abatement cost curves (MACC), an assessment is made for each of the reference vessels, and for different scenarios:

- No-regret: Only the cost effective abatement measures are applied. This means that for each individual measure on an annual basis, the saving in energy consumption are larger than the investment costs (including capital & maintenance costs). So each measure has a positive effect on the Total Costs of Ownership (TCO)
- Zero-cost scenario: Both cost effective and not cost effective measures are added, up to the point where the TCO is the same as for the reference ship. In terms of MACCs, this point is reached when the positive ΔTCO exceeds the value of the most negative ΔTCO.
- Maximum-saving: The maximum-savings potential is determined by calculating the sum of all abatement options.

The derived savings potentials for the three scenarios (no-regret, zero-cost and maximum-saving) are given in Table 24. This is done for the three different fuel prices:

- 1000 EUR/ton (high price scenario)
- 500 EUR/ton (medium price scenario)
- 250 EUR/ton (low price scenario)

Table 24: GHG emission reduction potential (%) for new-built ships for the different scenarios:

% CO_2 saving	**no regret**			**zero cost**			**maximal abatement**
Fuel price (EUR/ton)	**250**	**500**	**1000**	**250**	**500**	**1000**	
vessel type							
Dry Bulk	28	52	53	54	59	59	59
General Cargo	18	18	23	20	26	42	45
Container	22	24	27	27	30	30	30
Reefer	7	13	23	14	25	25	30
Ro-Ro & Vehicle	24	36	38	35	44	44	46
Oil Tanker, mainly crude	29	49	54	51	51	51	55
Oil Tanker, mainly product	23	23	28	27	33	45	49
Chemicals	21	41	41	28	45	45	45
LNG & LPG	13	13	27	19	30	30	30
RoPax	0	17	25	0	27	27	30

Main observations: Dark grey cells means that the maximal abatement is achieved before the zero cost point is reached, i.e. the total cost of all measures is smaller than the economic savings on fuel.

The total cost including operational cost, the additional capex of the selected abatement options and fuel is always lowest for the no regret scenario, i.e. reducing emissions is hence profitable compared to business as usual (BAU). Also for the maximum abatement scenario, taking into account the assessed abatement options, the TCO is in 8 out of 10 cases lower than the TCO of the reference vessels (cells with grey background). Only for general cargo ships and for small oil tankers (product tankers), there is actually an increase in TCO with all abatement measures implemented.

The following observations are made regarding the potential 2030 GHG savings for new ships:

- Based on the middle fuel price of 500 EUR/ton, in a no-regret scenario, the total GHG savings potential is between 15% and 50%, depending on the vessel category. In a zero-cost scenario (or better) GHG savings ranges from about 25% to 60% depending on the vessel category. For a number of categories the maximal abatement is achieved with a costs reduction.
- Based on the low price, 250 EUR/ton, the no regret savings ranges from 0% to 29% depending on vessel category.
- Based on the high price, 1000 EUR/ton, the no regret saving is 23% to 54%.
- In a maximum-reduction scenario, the total GHG savings potential is between 30% and 59%, depending on the vessel category. For 8 out of 10 vessel categories, the maximal abatement is achieved at a net saving compared to the reference scenario.

When projecting the total GHG emissions based on the different scenarios, it should be taken into account that only a part of the 2030 vessel fleet will consist of new ships on which all abatement measures can be applied (up to the boundary conditions of the scenario). On older, existing vessels (build before 2015), it is assumed that only the operational measures are applied. The operational measures add up to about 50% of the total measures. For other vessels, i.e. Ferry Pax; Cruise; Yacht; Offshore; Service; Fishing and other (unspecified) we assume that the abatement potential is 50% of the average for the cargo vessels. The explanation is that these vessels are much smaller, i.e. 560 dwt versus 30 800 dwt today and 600 dwt versus 42 500 dwt in 2030. This implies that not all measures which are cost effective on large vessels will be cost effective on smaller vessels. In table 25, the global scenario's are presented taking into account the different market shares for implemented measures on new and on existing ships (on the latter category only operational measures).

Table 25: 2030 global GHG emissions in thousand ton, per vessel category for the different abatement scenarios

kton/a $CO_{2\ equivalent}$	Reference: EOS + EEDI + LNG	Reference + no regret measures with different fuel prices (2030)			Reference + zero cost measures with different fuel prices (2030)			Reference + max abatement
Vessel type	2030	250 EUR/ton	500 EUR/ton	1000 EUR/ton	250 EUR/ton	500 EUR/ton	1000 EUR/ton	2030
Dry Bulk	279 058	220 456	170 226	168 133	166 040	155 575	155 575	155 575
General Cargo	130 507	112 889	112 889	107 995	110 931	105 058	89 397	86 461
Container	316 475	264 256	259 509	252 388	252 388	245 268	245 268	245 268
Reefer	35 995	34 106	32 486	29 786	32 216	29 246	27 896	27 896
RoRo & Vehicle	103 944	85 234	75 879	74 320	76 658	69 642	68 083	68 083
Oil Tanker > 80'dwt, crude	150 930	118 103	95 463	89 803	93 199	88 671	88 671	88 671
Oil Tankers < 80'dwt, product	88 367	73 124	73 124	69 810	70 473	66 496	58 543	55 892
Chemicals	94 354	79 493	65 340	65 340	74 540	62 510	62 510	62 510
LNG & LPG	82 169	74 157	74 157	65 530	70 460	63 681	63 681	63 681
RoPax	65 446	65 446	57 102	53 175	65 446	52 193	50 721	50 721
Cargo Vessels	1347 200	1127 300	1016 200	976 300	1012 400	938 300	910 300	904 800
Ferry-Pax only	21 847	20 064	19 164	18 840	19 133	18 532	18 305	18 260
Cruise	62 655	57 541	54 958	54 030	54 870	53 146	52 495	52 367
Yacht	6 402	5 880	5 616	5 521	5 607	5 430	5 364	5 351
Offshore	52 838	48 526	46 347	45 565	46 273	44 819	44 270	44 162
Service	63 232	58 072	55 464	54 528	55 375	53 636	52 979	52 850
Fishing	96 418	88 549	84 573	83 145	84 437	81 786	80 784	80 587
Other	14 437	13 258	12 663	12 449	12 643	12 246	12 096	12 066
Other Vessels	317 800	291 900	278 800	274 100	278 300	269 600	266 300	265 600
All Vessels	1665 000	1419 200	1295 000	1250 400	1290 700	1207 900	1176 600	1170 400
average reduction cargo vessels		16.3%	24.6%	27.5%	24.9%	30.4%	32.4%	32.8%
average reduction all vessels		14.8%	22.2%	24.9%	22.5%	27.5%	29.3%	29.7%

Based on table 25, and comparing the results with the reference scenario, the following conclusions can be made for the global emissions from shipping in 2030:

- With the no regret abatement measures, the GHG and energy saving potential is in the range of 15% to 25% (compared to the reference scenario) depending on the fuel price, and 16% to 28% for cargo vessels only.
- With zero cost abatement measures, the GHG and energy saving potential is in the range of 23% to 29% depending on the fuel price, and 25% to 32% for cargo vessels only.
- The maximum abatement potential, combining all cost effective and not cost effective measures leads to a saving potential of 33% for the cargo vessels and 30% for the entire fleet. The CO_2 emissions for the global maritime transport are then reduced from 1.6 to 1.7 billion ton in the reference scenario to 1.1 to 1.2 billion ton for the scenario with all abatement measures implemented. In comparison the 2012 emissions (Smith et al., 2014) is 0.95 billion ton for a freight work which is 50% of the expected 2030 level and which implies that 2030 emissions will be reduced by 40% per ton nm compared to 2012.
- For no regret measure, with the middle fuel price (EUR 500/ton), the global CO_2 emissions are reduced to 1.2 to 1.3 billion ton in 2030.

- With the zero cost scenario and the middle fuel price (EUR 500/ton), the global CO_2 emissions are reduced to about 1.2 billion ton in 2030.
- With a fuel price of 1000 EUR/ton, for most vessel categories all abatement measures will be applied under the zero cost scenario.

Based on table 25, the potential GHG savings for the global abatement scenarios are calculated and presented in Figure 20. This is done for the middle fuel price of 500 Euro/ton and it includes technical measures on new ships and operational measures on new and on existing ships.

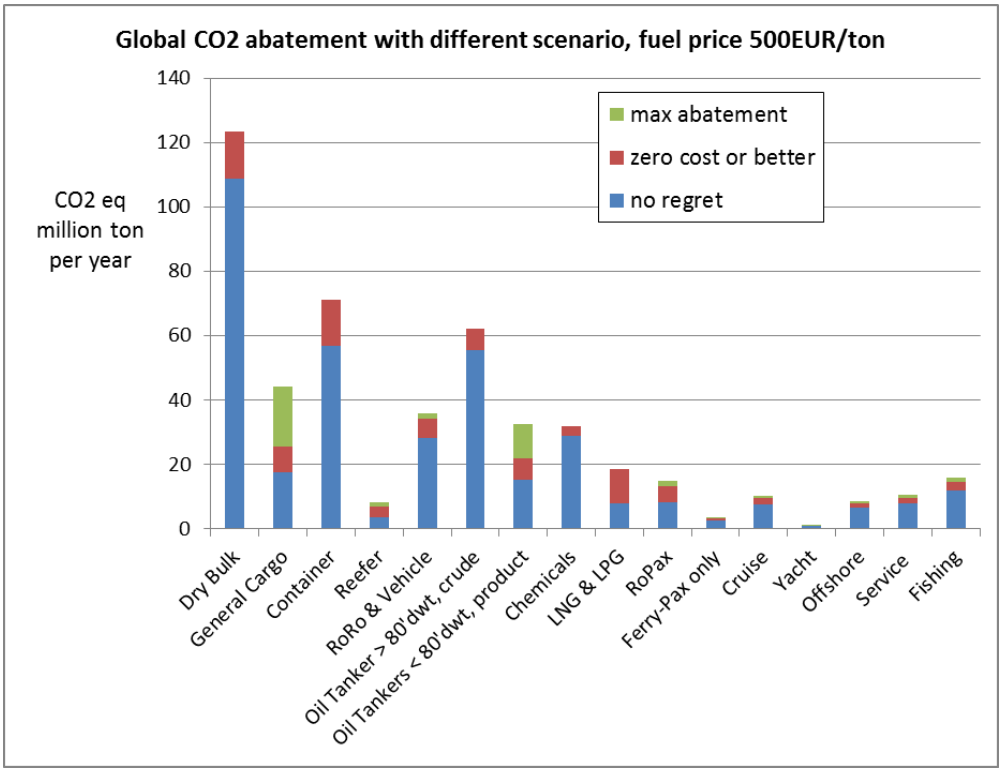


Figure 20: Potential GHG savings of Global maritime transport per vessel type in 2030

4.10 Abatement scenarios for Europe

In section 3.4.5, a projection for the European share of the global emissions was made. This was based on the lower GDP growth rate of 1.55% for Europe, compared to the global growth rate of 4.25%. This resulted in the European reference scenario with a total CO_2 emission of 208 million ton. The abatement scenario are consequently added to the European baseline. The results are presented in table 26.

Table 26: CO_2 emission European maritime transport for GHG abatement scenarios

2030	GHG emissions in million ton $CO_{2\ equivalent}$		
Baseline	251		
Reference- EOS + EEDI + LNG	208		
Abatement measures			
with fuel price	250 EUR/ton	500 EUR/ton	1000 EUR/ton
No regret	177	162	156
Zero cost	161	151	147
Max abatement	146		

Table 26 shows that for the middle fuel price (500 EUR/ton), the CO_2 emissions of the European maritime transport can be reduced from 208 million ton for the reference scenario, to 162 million ton with the implementation of the no regret abatement measures. This is a reduction of 22% compared to the reference scenario, which already includes the emission reductions due to Economy of Scale, EEDI and LNG. Compared to the baseline, i.e. the 2012 fleet characteristics without the effects of EOS; EEDI and LNG the reduction is around 35%. For the intermediate periods with reference years 2020 and 2025, the GHG emissions are calculated based on the yearly economic growth of 1.55%, the projected share of new build ships and a growing implementation of operational abatement measures on existing vessels. The results are as presented in figure 21.

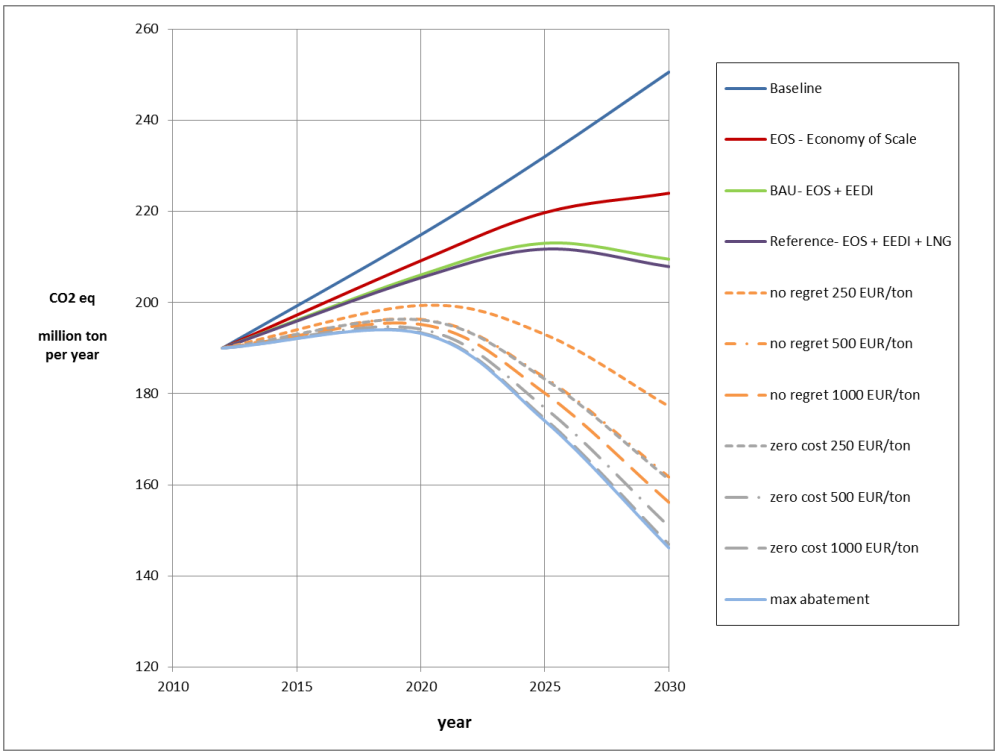


Figure 21: European maritime transport emissions for the assessed abatement scenarios.

The main observations from figure 21 are:

- With no regret abatement measures, the European maritime CO_2 emissions can be lowered from 208 million ton (reference scenario) to between about 156 and 177 million ton depending on the fuel price. This is 15% to 25% reduction compared to the reference scenario. The reduction is then 7% to 18% compared to the 2012 levels.

- With zero costs abatement measures, the CO_2 emissions can be reduced to about 147 to 161 million ton depending on the fuel price. This is a 23% to 29% reduction compared to the reference scenario (and 15% to 23% compared to 2012).
- With maximal abatement, the CO_2 emissions can be reduced to about 146 million ton CO_2 eq. This corresponds to a reduction of 30% compared to the reference scenario.

- Depending on the abatement scenario, the CO_2 emissions will continue to rice until around 2020. After that they will actually go down despite the yearly growth of transport volume (1.55%). This due to the increase share of new ships with abatement measures implemented and due to the implementation of operational measures in existing vessels.

4.11 Additional abatement measures with alternative fuels and cold ironing

The following measures are added to the operational and technical measures (sections 3.4 and 3.5):

- Higher take up of LNG as fuel (10% LNG share is already included in the reference scenario).
- Biofuel blend: the total amount of biofuel used is measure for the CO_2 reduction and not the blend ratio itself. E.g. a 4% biofuel blend in diesel for the entire fleet gives the same overall CO_2 reduction as a 10% blend for 40% of the fleet
- H_2 fuel cell for auxiliary power during sailing and optionally also when in ashore.
- Cold Ironing: Electric power from the electricity grid, when the ship is ashore.

For the latter three, the CO_2 reduction is quite dependent on the production options. For example H_2 and electric energy produced from fossil fuel or from a renewable source. The CO_2 reductions for these fuels are based on projections for the Dutch fuel mix assessment for 2030[5].

For this study, the following assumption are made:

- LNG: 8% CO_2 reduction. Refer to table 15.
- Biodiesel: 58% CO_2 reduction based on a well to propeller assessment.
- H2: 42% CO_2 reduction (per MJ of fuel energy). To achieve this, about 50% of the H2 must be produced from solar or wind power. Additionally a 10% higher energy efficiency is assumed for the fuel cell in comparison to a diesel generator set. In total the CO_2 reduction is about 48% (for the auxiliary power consumption).

[5] Dutch national program to evaluate fuel option for CO2 reduction in the future for all modes of transport. . http://www.energieakkoordser.nl/nieuws/brandstofvisie.aspx. 30 June 2014

- Cold ironing: 62% CO_2 reduction. To achieve this 35% to 50% of the electricity must be produced from solar or wind power.

The fuel prices and the investment and maintenance costs, determine the Total Costs of Ownership (TCO) and consequently the CO_2 abatement costs. For the investment costs, refer to table 23 in section 4.8. The fuel prices are based on the following sources:

- LNG: several sources which project or assume LNG prices far below to up to 30% above the HFO price.
- Biodiesel and H2: based on the Dutch fuel mix assessment5
- Electricity: price list wall power internet.

This results in the energy price assumption presented in table 27 below.

Table 27: CO_2 emission European maritime transport for GHG abatement scenarios

Fuel costs	HFO	LNG	Biofuels	H_2	Electricity
	€/ton diesel	€/ton diesel eq.	€/ton diesel eq.	€/ton diesel eq.	€/ kWh
Average	500	500	900	653	0.21
Low		350	800	457	0.12
High		650	1000	848	0.30

Consequently the CO_2 reductions and fuel prices assumption are used to calculate the abatement costs per ton tonne of CO_2 for an average ship. This is presented in Figure 22 below.

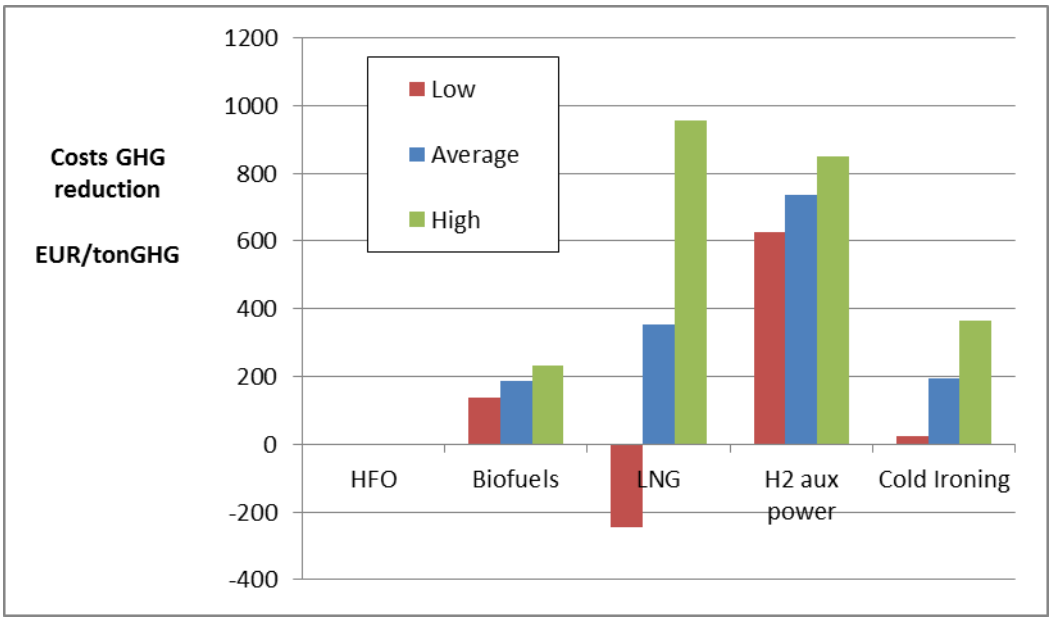


Figure 22. Costs for GHG reduction for several options with alternative fuels and cold ironing

Comparing the results of figure 22, with the operational and technical measures shown in the cost curves, the following observations can be made:

- LNG shows a very wide cost effectiveness range from profitable to one of the most expensive options depending on the LNG fuel price.
- H_2 fuel cells as CO_2 abatement measure is always quite expensive with a CO_2 reduction costs of 600 to 800 Euro per ton of CO_2 reduced.
- Biofuels and cold ironing are reasonable cost effective with around 200 Euro per ton of CO_2 reduced.

For making a projection of the overall CO_2 reduction for the European maritime transport, assumptions need to be done for achievable market shares. These are presented in table 28.

Table 28: Assumptions for potential market shares for alternative fuels and cold ironing.

Alternative fuel	(Additional) Market share	Overall energy share	Total GHG saving
LNG	25%*	25%	2.0%
Biofuel	4%	4%	2.3%
H_2 fuel cell for auxiliary power	12.5% **	2%	0.9%
Cold Ironing	25%	2%	1.2%

* On top of the market share within the reference scenario (around 10%).
** H_2 fuel cell used during sailing and ashore. If only used during sailing, then about 25% of the ships need to be converted.

Adding up the GHG savings presented in table 28, a further reduction of about 6.3% of the total CO_2 emissions can be achieved. This is include in table 29 and figure 23 below.

Table 29: CO_2 emission European maritime transport for GHG abatement scenarios, including additional use of LNG, biofuels, H2 fuel cells and cold ironing.

2030	GHG emissions in million ton $CO_{2\ equivalent}$		
Baseline	251		
Reference- EOS + EEDI + LNG	208		
Abatement measures			
with fuel price	250 EUR/ton	500 EUR/ton	1000 EUR/ton
No regret	177	162	156
Zero cost	161	151	147
Max abatement	146		
Max abatement + alternative fuels + cold ironing	137		

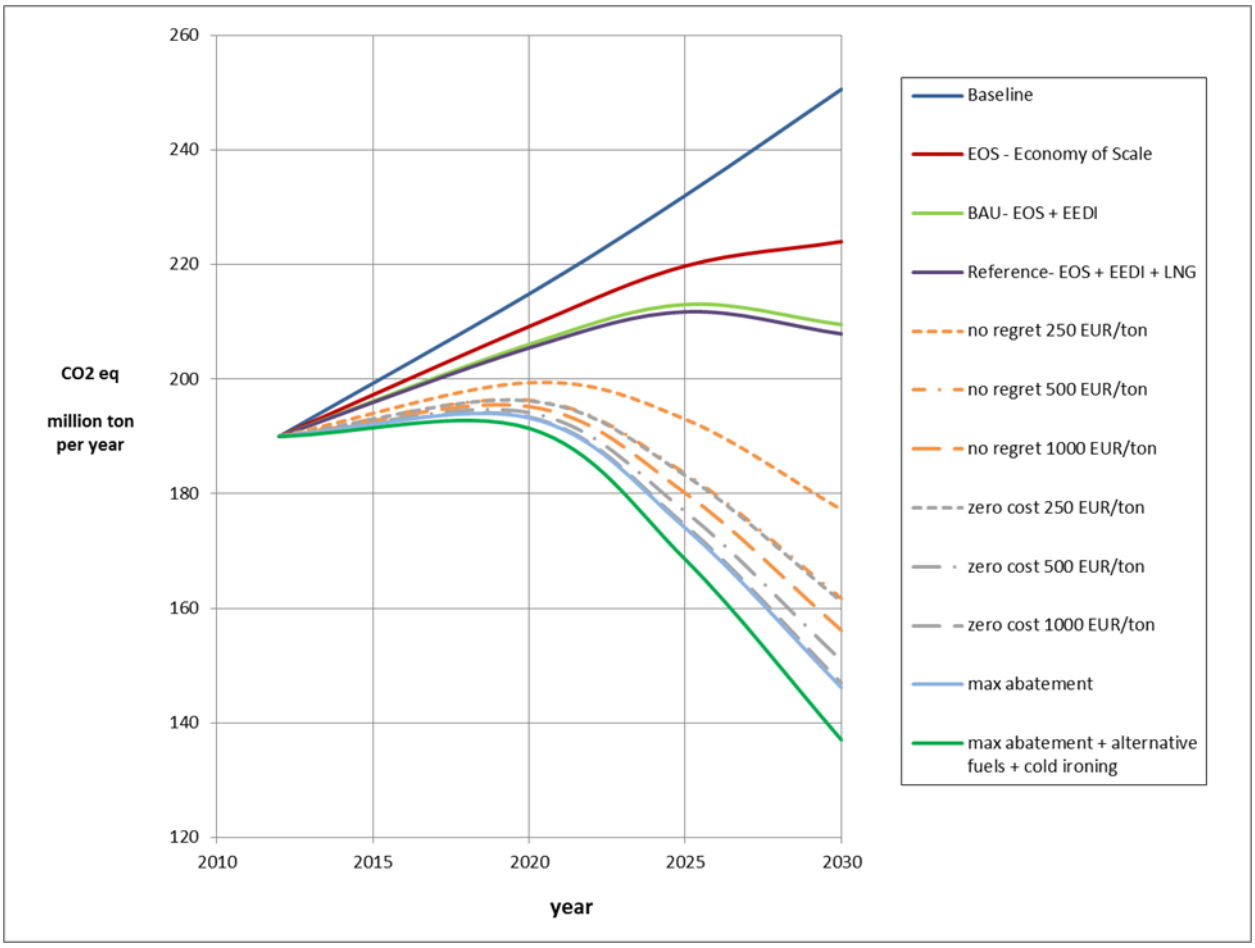


Figure 23. European maritime transport emissions for the assessed abatement scenarios, including additional use of alternative fuels (LNG, biofuels H2 fuel cells) and cold ironing.

4.12 Previous studies of Marginal Abatement Costs

In this section a comparisonis made of this study and previous studies of Marginal Abatement Costs Within the shipping at least four MAC curves have been previously published:

- The Second IMO GHG study (Buhaug et al., 2009)
- Technical Support for European action to reduce reducing Greenhouse Gas Emissions from international maritime transport (Faber et al., 2009)
- Pathway to Low Carbon shipping (DNV, 2010)
- IMAREST - Marginal Abatement Cost and Cost Effectiveness of Energy-Efficiency Measures (MEPC 61/INF18)

A previously described, all these studies are primarily based on shipping as it operated before the 2008 financial crisis, i.e. higher speeds and with less focus on environmental performance than seen today.

Figure 24 shows the marginal abatement cost curve for international shipping in 2020 developed by The Second IMO GHG study (Buhaug et al., 2009).

The figure indicates that the no regret abatement measures add up to around 25% reductions, i.e. the central estimate compared business as usual (BAU) based on a fuel price of 500 USD per ton.

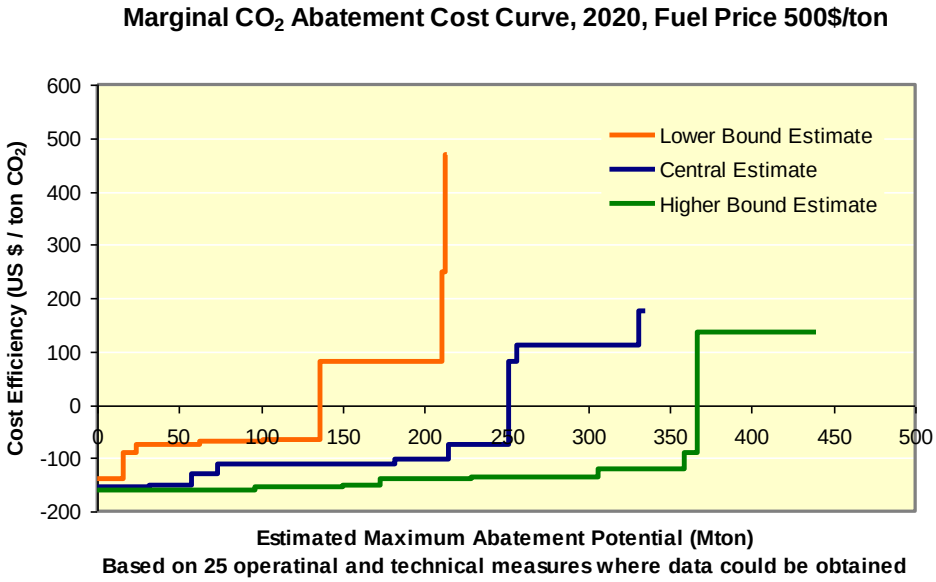


Figure 24: Indicative marginal CO_2 abatement costs for 2020 (source: Buhaug et al 2009)

Figure 25 shows the marginal abatement cost curve for international shipping in 2030 as calculated by the Technical Support for European action to reduce reducing Greenhouse Gas Emissions from international maritime transport (Faber et al., 2009). The figure indicates that the no regret abatement measures add up to around 30 – 35% reductions, i.e. the central estimate compared to business as usual (BAU) based on a fuel price of 700 USD per ton.

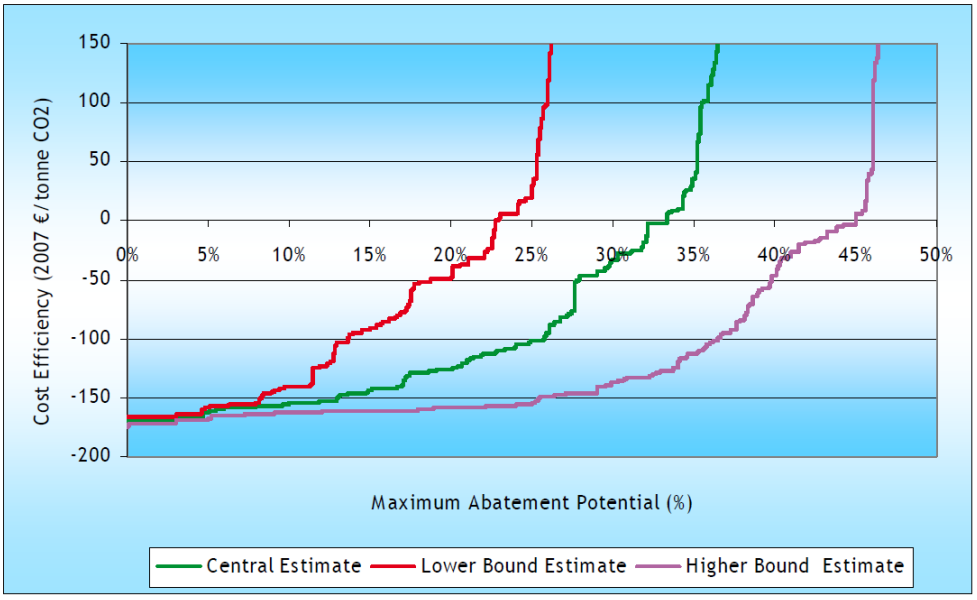


Figure 25: Indicative marginal CO_2 abatement costs for 2030 (source: Faber et al., 2009)

Figure 25 shows the marginal abatement cost curve for world shipping fleet in 2030 from the Pathway to Low Carbon shipping study (DNV, 2010). The figure indicates that the no regret abatement measures add up to around 30% reductions compared business as usual (BAU) based on a fuel price of 350 USD per ton for HFO and LNG and 500 USD per ton for MDO. And that the maximum abatement potential is 37%.

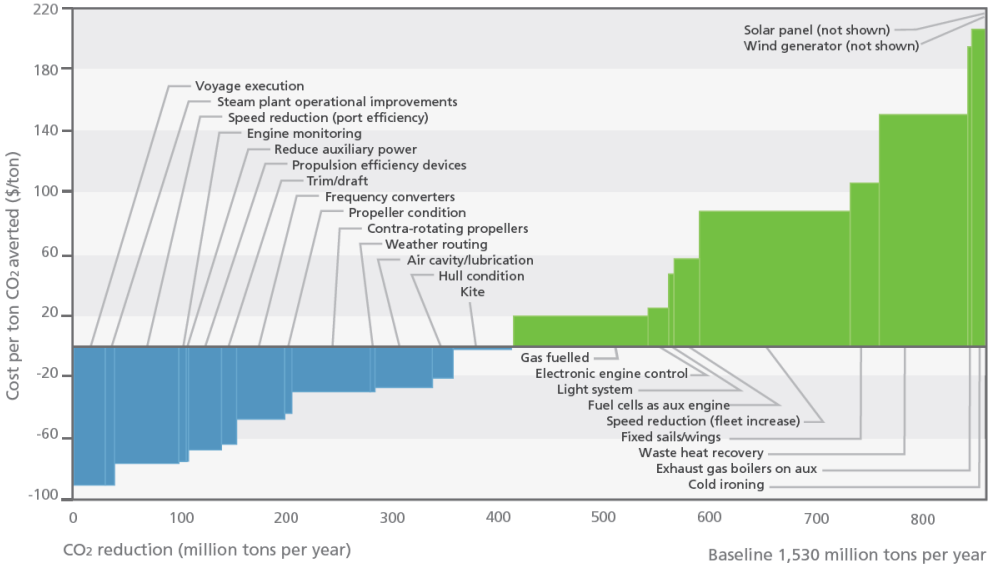
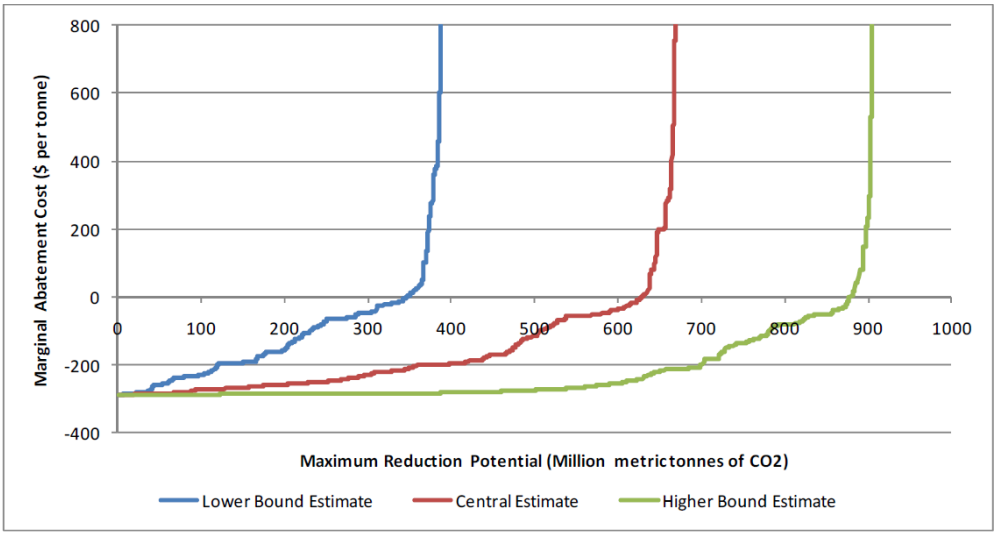


Figure 26: Indicative marginal CO_2 abatement costs for 2030 (source: DNV, 2010)

Figure 27 shows the marginal abatement cost curve for world shipping fleet in 2030 in the IMAREST study Marginal Abatement Cost and Cost Effectiveness of Energy-Efficiency Measures (MEPC 61/INF18). The figure indicates that the no regret abatement measures add up to around 27% compared to business as usual based on a fuel price of 700 USD per ton. And that the maximum abatement potential is less than 35%.



Source: IMAREST, 2010a.

Figure 27: Indicative marginal CO_2 abatement costs for 2030 (source: IMAREST, 2010)

According to the IMAREST study MACC curves are sensitive to:

- The projected price of the 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 MACC studies, we have compared the assumptions, see table 30.

Table 30: Quantitative comparison of MACC studies

Study	Fuel Price	Discount Rate	Percentage reduction at no regret cost	Maximum Abatement potential
IMO 2009 GHG	500 USD/ton		25%	
Faber et al 2009	700 USD/ton	9%	30%	37%
DNV, 2010	350 USD/ton HFO &LNG 500 USD/ton MDO	8%	30%	56%
IMAREST	700 USD/ton	10%	25%	37%
This Study compared to 2030 reference scenario	300 USD/ton (250 EUR/ton)	8%	15%	30%
	600 USD/ton (500 EUR/ton)	8%	22%	30%
	1200 USD/ton (1000 EUR/ton)	8%	25%	30%
This Study compared to 2030 baseline	300 USD/ton (250 EUR/ton)	8%	29%	42%
	600 USD/ton (500 EUR/ton)	8%	35%	42%
	1200 USD/ton (1000 EUR/ton)	8%	38%	42%

To summarize:

- All studies shows no regret cost of the same magnitude;
- The DNC study shows the highest maximum potential which can be explained by the fact that it includes the longest list of abatement measures;
- In comparison several of these measures have been excluded from this study since they have already been implemented.

4.13 Conclusions

In Section 3, a reference scenario was developed for the GHG emissions of global and European maritime transport between 2012 and 2030. The reference scenario included the Economy of Scale (gradual growth of average ship size), the implementation of the EEDI and the gradual application of LNG.

With the reference scenario, the European maritime GHG emissions in 2030 total about 415 million ton of CO_2 annually. If the same transport capacity would be transported with the 2012 vessel characteristics, the annual CO_2 emission would be about 600 million ton.

In this Section 4, costs-benefit of a range of abatement measures have been evaluated for 10 vessel categories. Consequently, they are modelled in Marginal Abatement Costs Curves (MACC) and a number of scenarios are modelled.

These scenarios include:

- No regret abatement: application of all abatement measures which (individually) save costs (lower TCO)
- Zero costs abatement: application of all abatement measures up to the point that the costs are the same as the reference
- Maximal abatement: application of all investigated abatement measures.

The first two scenarios were processed for three fuel prices: 250, 500 and 1000 EUR/ton diesel equivalent.

The abatement measures include both technical measures and operational measures. For the future projection it is assumed that both types of measures will be applied to new ships, and that operation measures will be applied to existing ships.

The work lead to the following conclusions regarding the potential GHG savings for new ships:

- Based on the middle fuel price of 500 EUR/ton, in a no-regret scenario, the total GHG savings potential is between 15% and 50%, depending on the vessel category. In a zero-cost scenario GHG savings ranges from about 25% to 60% depending on the vessel category. For a number of categories the maximal abatement is achieved with a costs reduction. This is dependent on the fuel price.
- Based on the low price, 250 EUR/ton, the no regret savings ranges from 0% to 29% depending on vessel category.
- Based on the high price, 1000 EUR/ton, this range becomes 23% to 54% savings.
- In a maximum-reduction scenario, the total GHG savings potential is between 30% and 59%, depending on the vessel category. For 8 out of 10 categories, the maximal abatement is achieved at a net saving compared to the reference scenario.

Taking into account, the measures that can be applied to new and existing ships, the following conclusions are drawn for the European GHG emissions of maritime transport for 2030:

- With no regret abatement measures, the 2030 European maritime CO_2 emissions can be lowered from 208 million ton (reference scenario) to between 156 and 177 million ton depending on the fuel price. This is 15% to 25% reduction compared to the reference scenario. The reduction is then 7% to 18% compared to the 2012 levels.
- With zero costs abatement measures, the CO_2 emissions can be reduced to 147 to 161 million ton depending on the fuel price.

This is a 23% to 29% reduction compared to the reference scenario (and 15% to 23% compared to 2012).

- With maximal abatement, the CO_2 emissions can be reduced to about 146 million ton CO_2 eq. This corresponds to a reduction of 30% compared to the reference scenario.
- With additional use of alternative fuels (LNG, biofuels, H2 fuel cells and cold ironing), the CO_2 emissions can be further reduced to about 137 million ton of CO_2 eq, a further reduction of about 6%.
- Depending on the abatement scenario, the CO_2 emissions would continue to rice until around 2020. After that they would actually go down despite the yearly growth of transport volume (1.55%). This due to the increase share of new ships with abatement measures implemented and due to the implementation of operational measures in existing vessels.

5. Pass through of costs and savings [task 4]

The main objective of task 4 is to identify for the most relevant commodities, the pass-through of savings to the different actors in the supply chain and to quantify these impacts according to the different scenarios and sub-scenarios established under task 3. As a part of this task we evaluate what will be the increase in costs when ships start to invest in more environmental friendly transportation methods by implementation of energy saving / CO_2 abatement measures. Transferring this extra cost directly to the price for the customer might lead to a decrease in demand. Depending on the scenario (no regret, zero costs and maximal abatement), the transportation costs decrease or increase. The question is therefore what will happen to the transportation price, the profit margin of the ship operator and the volume of transported goods (per segment) if the different CO_2 abatement measures are implemented. The objective of task 4 is to analyze this and determine what the passing on of savings or costs is from the shipping company to the costumer.

Market power will affect the extent to which savings can be kept in the own sector. For instance when there is heavy competition in the sector, the savings will pass-through in order to reduce the consumer prices to a competitive level.

Based on these data, the incidence of the cost savings to ship operators or the final consumer will be evaluated, refer to figure 28 (from the tender specifications), which singles out three possibilities of saving pass-through:

1. Savings or costs are kept by the ship-operators if maritime transport is demand inelastic;
2. Savings or costs are kept by the shippers if the maritime transport is demand elastic and demand of commodities using maritime transport is inelastic;
3. Savings or costs are passed through to the final consumer if both the transport demand and demand of commodities are elastic.

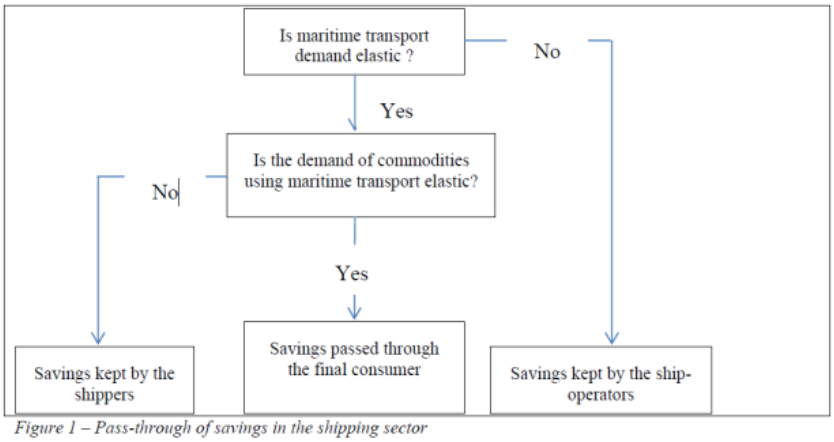


Figure 1 – Pass-through of savings in the shipping sector

Figure 28: Pass through of savings (or costs) in the shipping sector. Source: tender specifications

A model, which takes into account the indicators above, determines the proportions of the allocation of savings between maritime-operators and final consumers. More specifically, the profit margin, the transportation price and the tonnages measured as ton nm transported (for the scenarios defined in task 3) are based on the following boundary conditions:

- The abatement measures are installed on 25% of the ships for all vessel types.
- The price elasticity of demand for the commodity typical for the different vessel types.
- Total fixed costs equals 12% of the vessel new-building price. This includes investment and financial costs and fixed annual operational costs such as personnel, maintenance and insurance costs.
- Marginal cost is equal to fuel costs per ton per nautical miles (nm).
- Price of shipping is calibrated by the assumption of 5% profit margin in the baseline situation.

The impacts on prices, profits and volumes are evaluated for the 10 vessel types that were used for the analysis in task 3:

1. Dry Bulk
2. General Cargo
3. Container 4000 TEU
4. Reefer
5. Ro-Ro & vehicle
6. Oil Tanker-mainly crude > 80' dwt
7. Oil Tankers-mainly product <80’ dwt
8. Chemicals
9. LNG & LPG
10. RoPax.

The analysis of impacts of various packages of improvement options have been done for the following scenarios:

1. No regret: only profitable abatement measures (fuel consumption costs savings are higher than investment and operational costs of each measure)
2. Zero cost: also not profitable measures are added up to the point that the Total Costs of Ownership (TCO) are the same as for the reference ship.
3. Maximal abatement.

For the description of the maritime market model and its results we use the following concepts: the ‘customer’ refers to the company that has a demand for transportation. The shipping company provides the transportation.

5.1 Description of the maritime market model

This section describes the applied model, i.e. the Constant Elasticity of Substitution utility model. The CES-utility model is a commonly used competition model, generally used to evaluate price equilibrium based on demands and costs functions (Varian 1992) [6].

[6] Hal Varian, *Microeconomic Analysis and Microeconomic Theory*, 3rd. Ed. W.W. Norton & Co., 1992

Customers switch between shipping and transportation by road when the price for shipping is too high. The CES-utility functions represents the customers utility and is given by $U(x,y) = (\alpha x^{\rho} + (1-\alpha)y^{\rho})^{1/\rho}$, x (maritime transportation) and y (transportation by road or rail) are the output levels, i.e. freight rates.
The constant elasticity of substitution is given by $\sigma = \frac{1}{1-\rho}$, and is an indication of the customers willingness to switch between the two transportation types. Parameter α denotes the share parameter.

Assume that budget $M = (p_x x + p_y y)$ is spend on transportation. Optimizing the CES-utility function under the budget constraint, results in the optimal output quantities:

$$x = \frac{M}{p_x + p_y(\frac{(1-\alpha)p_x}{\alpha p_y})^{\sigma}} = \frac{\left(\frac{p_x}{\alpha}\right)^{-\sigma} M}{\alpha p_x^{1-\sigma} + (1-\alpha)^{\sigma} p_y^{1-\sigma}} \text{ and } y = \frac{\left(\frac{p_y}{1-\alpha}\right)^{-\sigma} M}{\alpha p_x^{1-\sigma} + (1-\alpha)^{\sigma} p_y^{1-\sigma}}.$$

From the exogenous data, we know $x, y, p_x, p_y,$ and $M = p_x x + p_y y$.

The input data for the different vessels categories and scenarios is summarized in Appendix C.
The assumption about the elasticity of substitution (modal shift) for the vessel types is taken exogenously and is given in Table 31. The values are based on an experts view by Marintek and TNO, based on the description from (Varian 1992). An elasticity of substitution bigger than 1 implies that the transportation alternatives are substitutes, elasticity of substitution smaller than 1 implies complements. And elasticity of substitution equal to 1 implies constant returns to scale, that is, an increase in the output in the shipping market results in an equivalent output increase in the total transportation market.

Table 31: Values for the elasticity of substitution (modal shift) used in the model.

	Elasticity of substitution
Dry bulk	0.1
General Cargo	0.9
Container 4000 TEU	0.9
Reefer	0.9
RoRo & vehicle	0.9
Oil Tanker-mainly crude > 80' dwt	0.1
Oil Tankers-mainly product < 80'dwt	0.5
Chemicals	0.5
LNG & LPG	0.5
RoPax	0.95

Solving the expression x for α, an estimate for α is found: $\alpha = \frac{1}{1+(\frac{y}{x})^{1/\sigma}(\frac{p_x}{p_y})}$.

For each vessel-type we solve the above problem. That is, for each vessel-type, we find a different level of α.

Both marginal costs and fixed costs change after implementation of several technical or operational measures. That is, the fixed costs will increase, and the marginal costs will decrease (due to efficient use of fuel). Take $i = \{N, O\}$, where N indicates 'new', and O indicates 'old', referring to the situation before and after the implementation of the efficiency measures.

Total costs of the shipping industry is: $TC_i = FC_i + x_i MC_i$.
Total revenue of the shipping industry is: $TR_i = xp_i$.
Total profit of the shipping industry is: $TP_i = TR_i - TC_i$.

Thus, we are able to compute the total profit for the case where no efficiency measures have been implemented. We assume that only 25% of the vessels shall implement the technical and operational measures.
The new prices are found by equalizing the profit before the efficiency implementation to the weighted profit after the efficiency implementations. That is, solve the following equation for p_N:

$$x_O p_O - FC_O - x_O MC_O = 0.25(x_N p_N - FC_N + x_N MC_N) + 0.75(x_N p_N - FC_O + x_N MC_O).$$

Basically, we need a baseline against which we compare the new situation, setting the weighted total profit after the cost-change equal to the profit in the initial situation should give realistic prices. Namely, the competitive market prevents shippers from setting a price that result in a higher profit than in the initial situation. The profit margin in the initial market is set to 5%, that is:

$$\frac{TP_O}{TR_O} = 0.05$$

For each vessel-type and scenario, new prices are found that will be charged to the customer.

The following main questions will be addressed:

1. How does the new price affect the customer, that is, will the price for the customer increase or decrease?
2. How does the new price affect the average profit margin for each vessel type, when the abatement measures are implemented on 25% of the vessels in the fleet.

5.2 Results of the maritime market model for three scenarios

In this section the results of the three scenarios developed in task 3 are calculated with the market model. The three scenarios are: 'no regret', 'zero-costs' and 'maximal abatement'.
The new (weighted) average profit margin is calculated based on the assumption that 25% of the vessels will be equipped with the abatement measures and that 75% of the vessel remain unchanged.

Table 32 shows the new average profit margins. The initial profit margin was set to 5% (profit divided by turnover). Profit margins lower than 5% are highlighted, indicating that those market segments are harmed by the changing situation (for clarity, Table 33 shows the new profit margin subtracted from the old profit margin).

For almost all vessel types, the ‘zero regret’ and ‘zero cost’ scenarios lead to a larger profit margin. Only under ‘maximal abatement’, where all technical and operational measures are implemented (no matter whether they are profitable), it is possible that the market observe a reduction in profit margin (margin lower than 5%). In that scenario, the fixed costs dominate the variable costs, thus implementing all abatement measures result in a decrease in profit.
An increase in price is then required to obtain the same average profit as in the initial market situation (this mainly raises the profit of those vessels that do not implement the changes, however the average profit is the same as before the implementation).

The results show that in most cases it is profitable for shipping companies to invest in part of the operational and technical CO_2 abatement measures according to the no regret or zero cost scenarios.
The relative changes in transport prices (customer prices) and transport volumes are presented in Table 34. When the price for customers increases, i.e. consumers are harmed by the new situation where measures are implemented, the value in Table 34 is highlighted in red.
Recall that the zero-cost scenario is defined as the point where both cost effective and not cost effective measures are added, up to the point where the TCO is the same as for the reference ship. These are however discrete steps such that the TCO is not exactly the same, but close. Moreover in several cases, the cost effective measures dominate resulting in a significant TCO benefit for the zero costs scenario. For this reason there is still some influence on price and volume in Table 34, also with the zero costs scenario.

For almost all vessel types (except Dry bulk), also consumers benefit from the decrease in variable costs, because it results in lower prices. Like mentioned before, under ‘maximal abatement’ prices are really high for six out of ten vessel segments, because the market should compensate for the 25% of total firms that implement unprofitable measures. In that case the customers pay a higher price for transportation.

For the vessel types; dry bulk, container 4000 TEU, oil tanker-mainly crude, and chemicals, the zero cost and maximal abatement scenarios are the same (same implemented measures). Consequently for those vessel types, the new average profit margins and prices changes are also the same. For vessel type ‘dry bulk’, the customer price increases slightly and the average profit margin decreases under the zero cost scenario. Even though the decrease in fuel costs is enough to compensate for the increase in fixed cost, still this vessel type faces a relatively large increase in fixed costs. Increases in fixed costs tend to be shared with the customer.

Table 32: Impacts on average profit margin for each vessel type, when the abatement measures are implemented on 25% of the vessels (based on 5% nominal profit margin before the installation of abatement measures).

	Average profit margin %		
	No regret	Zero cost	Maximal abatement
Dry bulk	5.078%	4.996%	4.996%
General Cargo	5.008%	5.006%	4.943%
Container 4000 TEU	5.012%	5.002%	5.002%
Reefer	5.007%	5.001%	4.976%
RoRo & vehicle	5.022%	5.000%	4.987%
OilTanker-mainly crude > 80' dwt	5.053%	5.024%	5.024%
OilTankers-mainly product < 80'dwt	5.013%	5.010%	4.923%
Chemicals	5.029%	5.004%	5.004%
LNG & LPG	5.015%	5.003%	4.988%
RoPax	5.001%	5.000%	4.994%

Table 33: Relative changes in the profit margins of maritime sector firms.

	Percentage point change in average profit margin		
	No regret	Zero cost	Maximal abatement
Dry bulk	0.078%	-0.004%	-0.004%
General Cargo	0.008%	0.006%	-0.057%
Container 4000 TEU	0.012%	0.002%	0.002%
Reefer	0.007%	0.001%	-0.024%
RoRo & vehicle	0.022%	0.000%	-0.013%
OilTanker-mainly crude > 80' dwt	0.053%	0.024%	0.024%
OilTankers-mainly product < 80'dwt	0.013%	0.010%	-0.077%
Chemicals	0.029%	0.004%	0.004%
LNG & LPG	0.015%	0.003%	-0.012%
RoPax	0.001%	0.000%	-0.006%

Table 34: Relative changes in transport consumer prices and transport volume per vessel segment.

	Percentage price change			Changes in output (transport volume)		
	No regret	Zero cost	Maximal abatement	No regret	Zero cost	Maximal abatement
Dry bulk	-3.7%	0.2%	0.2%	2.3%	-0.1%	-0.1%
General Cargo	-3.1%	-2.4%	26.5%	3.1%	2.4%	-20.0%
Container 4000 TEU	-3.3%	-0.5%	-0.5%	3.2%	0.4%	0.4%
Reefer	-1.7%	-0.3%	6.4%	1.6%	0.2%	-5.6%
RoRo & vehicle	-4.8%	-0.1%	3.0%	4.6%	0.1%	-2.7%
OilTanker-mainly crude > 80' dwt	-4.0%	-1.9%	-1.9%	3.1%	1.4%	1.4%
OilTankers-mainly product < 80'dwt	-2.4%	-1.8%	16.5%	2.2%	1.6%	-12.8%
Chemicals	-2.8%	-0.4%	-0.4%	2.3%	0.3%	0.3%
LNG & LPG	-1.8%	-0.4%	1.6%	1.6%	0.3%	-1.3%
RoPax	-1.1%	-0.1%	5.7%	1.1%	0.1%	-5.3%

Table 35 shows the percentage changes in average costs. Comparison of Table 32 and 34 with Table 35 shows that a decrease in profit margin and an increase in customer price always corresponds to an increase in average costs. This is due to the lower transportation volume, i.e. the increased fixed costs have to be shared between less transportation volume. This will occur under maximal abatement, where all operational and technical measures are implemented, despite it is not profitable for all vessel types.

For completeness, Table 36 shows the average costs in euros for the initial situation and all situations ('no regret', 'zero cost' and 'maximal abatement') after the measures are implemented.

Table 35: Relative changes in average transportation costs

	Percentage change in costs per ton per nautical mile		
	No regret	Zero cost	Maximal abatement
Dry bulk	-3.8%	0.2%	0.2%
General Cargo	-3.1%	-2.4%	26.6%
Container 4000 TEU	-3.3%	-0.5%	-0.5%
Reefer	-1.7%	-0.3%	6.5%
RoRo & vehicle	-4.8%	-0.1%	3.0%
OilTanker-mainly crude > 80' dwt	-4.1%	-1.9%	-1.9%
OilTankers-mainly product < 80'dwt	-2.4%	-1.8%	16.6%
Chemicals	-2.8%	-0.4%	-0.4%
LNG & LPG	-1.8%	-0.3%	1.6%
RoPax	-1.1%	-0.1%	5.8%

Table 36: Average costs in Euros for the three scenarios

	Costs per ton per nautical miles (before implemented measures)	Costs per ton per nautical mile (after implemented measures)		
	EURO	No regret	Zero cost	Maximal abatement
Dry bulk	0.0025	0.0024	0.0025	0.0025
General Cargo	0.0170	0.0164	0.0166	0.0215
Container 4000 TEU	0.0061	0.0059	0.0060	0.0060
Reefer	0.0173	0.0170	0.0172	0.0184
RoRo & vehicle	0.0128	0.0122	0.0128	0.0132
OilTanker-mainly crude > 80' dwt	0.0025	0.0024	0.0025	0.0025
OilTankers-mainly product < 80'dwt	0.0177	0.0172	0.0173	0.0206
Chemicals	0.0078	0.0076	0.0078	0.0078
LNG & LPG	0.0044	0.0043	0.0044	0.0045
RoPax	0.1742	0.1723	0.1741	0.1842

5.3 Conclusions

For the pass-through of savings or costs from shipping companies to its customers, a model has been built to evaluate this based on price elasticity of the market segment and the assumption that the abatement measures has been implemented on 25% of the shipping fleet. This leads to the following conclusions:

- Savings and costs due to CO_2 abatement measures are usually shared between shipping company and its customers.
- For almost all vessel types, both shipping companies and its customers benefit from the abatement measures under the scenario ‘no regret’ and ‘zero cost’, because it results in lower prices and an increased profit margin for the transportation company. Price reductions range from about 0.1% to almost 4%, while the average profit margin would increase by 0.1% point or less (nominal 5%).
- Under the ‘maximal abatement’ scenario, the prices would increase up to 26% (for general cargo, but mostly below 10%) and the profit margins are reduced by about 0.08% point or less. In general, scenarios where a shipping company decides to increase the customer price to maximise his profit margin, corresponds to a lower average profit margin. We can conclude that losses are both incurred by the firm itself and shared with the customer.

6. Impacts on the third countries [task 5]

The goal of task 5 is to estimate impact on non-EEA countries by the GHG emission reduction scenarios. Given that the analysis of maritime transport flows in tasks 2 and task 3 does not differentiate between the origin and destination of the flows we are not able to provide the quantitative estimates of the impacts on them. Instead we can propose some analysis based on the general results of the quantification with the maritime market model developed for this project.

For almost all vessel types, scenario ‘zero regret’ and ‘zero cost’ lead to a larger profit margin. Only under ‘maximal abatement’, where all technical and operational measures are implemented (no matter whether they are profitable), it is possible that the shipping companies observe a profit margin lower than 5%. The effect on its customers is reflected by the impact on the price. If the price for consumers increases, the customer is harmed by the new situation. And if the price for consumers decreases, the customer is benefitting from the abatement measures implemented.

For all vessel types , also customers in third countries benefit from the decrease in variable costs under the No regret and the Zero cost scenario, because it results in lower prices. And even for the Maximal abatement scenario the price increase is marginal with two exceptions which are General Cargo and oil tankers& product tankers below 80 000 dwt. For these vessel types , the increase in fixed costs are relatively large.

In case of the third countries – for the 'no regret' and the 'zero cost' scenario, the extent consumers will benefit from the proposed technical improvement measures, will also depend on the composition of the vessel/commodity types that they demand. Only if the share of general cargo and oil tankers-mainly product <80’ dwt is high for the third countries under the maximal abatement scenario (which considers that all technically feasible measures are implemented regardless their costs), their customers would face an increase in their prices

In previous studies, the analyses were based on the assumption that measures to reduce GHG emissions from maritime transport would lead to additional costs. Obviously, this leads to results identifying negative impacts on third countries (increasing shipping costs). Nevertheless, an overview of the results of previous studies is provided below, in particular because some of them allow for regional differentiation.

In 2009 Faber et al. (2009) concluded that: *The assessment has shown that impacts for small island developing states, least developed countries and landlocked developing countries will be low to very low under realistic assumptions. Only under very specific circumstances could EU policy addressing emissions from international maritime transport affect these countries in a noticeable way. Despite this, the effect for individual countries with specific circumstances might be higher.*

In 2011 PWC in a study for Norwegian Ship owners Association quoted that: *Developing and least developed countries whose trade in price-sensitive goods often comprises a significant component of their export potential might suffer disproportionately from an increase in trading costs (WTO, 2003). The OECD identified several countries, mostly remote nations with very small markets, face*

such high transport costs that they affect most exports significantly. Average ad valorem maritime transport costs of exports for Guam(48%), Nauru (40%), Christmas Islands (34%), Togo (29%), Guinea (25%), Tonga (22%), Sierra Leone (21 %) and Pitcairn (17%) were found to be substantially higher than the average for developing countries of 7 % (OECD, 2008).

In 2013 AEA-Ricardo in a study for DG-Clima found that: *In 2010, least developed countries (LDCs) represented a very small proportion of EU seaborne imports (2% of the value and 2.9% of the total volume). They also accounted for 4.7% of extra-EU seaborne exports' value and 2.8% of volume. While LDCs play a small role in the EU's seaborne trade, the EU may play a large role in theirs, offering a large market and sources of revenues to their economy through these imports. This would make them all the more sensitive to a change in shipping costs. Bangladesh, Angola, Equatorial Guinea, Mozambique and Cambodia are the main LDC exporters to Europe, whilst Angola, Senegal, Bangladesh, Benin and Yemen and the main importers from Europe.*

Again, these studies have been based on the assumption that that measures to reduce GHG emissions from maritime transport would lead to additional costs. This assumption is not supported by the results of this study which demonstrates that under the 'no regret' and 'zero costs' scenarios and even for certain ship types under the 'maximum abatement' scenario net costs will be reduced due to significantly reduced fuel bills. Therefore, the countries and regions analyzed by the above studies would benefit from any regulatory or other measure to reduce GHG emissions from shipping which stays below the 'maximum abatement' scenario. Small/ large negative impacts identified by those studies have to be translated into small/ large positive impacts.

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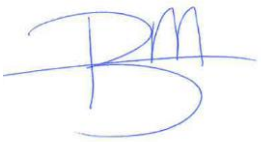
8. Signature

Delft, 3 July 2015



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A Fleet projection for different vessel segments

The objective of tasks 1.1 is to provide a fleet projection until 2030 – separated in 5-years-periods for 2010 (baseline), 2015, 2020, 2025 and finally 2030. The reason behind is that the fleet composition is changing in different ways, so not only in terms of size but also in terms of energy efficiency due to various reasons[7]. Hence, it is necessary to have projection on the fleet to calculate in the following tasks the ship-related air emissions.
As emissions vary among the different vessel types, the following segments have been identified presenting the relevant fleet for the analysis of GHG emission reduction potentials.

Relevant fleet segments[8]:
- container vessels
- dry bulk carriers
- general cargo / general cargo reefer
- general cargo roro
- oil/chemical and chemical tanker
- crude and product tankers
- ferries
- cruise ships
- private yachts
- off shore supply vessels

The fleet segments are split in two groups:
- The regular segments which are already included in the MOVEET fleet model (the first 6 of the list).
- Special fleet segments: ferries, cruise ships, private yachts and off-shore supply vessels.

Standard fleet segments

Following the determination of the fleet segments, variables had to be defined which are determining the ship emissions. The CO_2 emissions of seagoing vessels are mainly determined by a set of variables.

In general the product of the fuel consumption and the individual CO_2 factor by fuel types shows the CO_2 emissions. Hence, for the calculation of the emissions a set of variables is necessary. These variables are the fuel type, the fuel consumption of the engine, the physical engine designed kW size, the load rate of the engine and the time of operation.

As fuel types there are different fuels in operation like HFO, MDO, MGO and LNG in different sea areas and for different ship types.

[7] see task 1.2 on drivers for ship emissions.
[8] The fleet segments have to be adjusted with the structure as used in the MOVEET model, i.e. minor adjustments within the fleet composition might be necessary in task 2.

The fuel consumption of the engine is defined as consumption in g/kWh. This fuel consumption of the engine is reported mainly by the engine producer for the service speed point of the ship, for the main engines and the standard operation of the auxiliaries engines.

The real total fuel consumption of the main engine depends on the load rate of the engine which can be calculated with a set of variables (like real speed of the ship, designed speed of the ship and designed kW size of the main engine).

In addition to the main engine a set of auxiliary engines is in operation of the ship. The total fuel consumption of these auxiliaries depends on the required energy consumption of the ship (for cargo cooling, cargo pumping, manoeuvre operation, etc.) and the specific fuel consumption of the auxiliary engine set.

Hence, the standard set of necessary variables
- main engine kW size,
- specific fuel consumption of the main engine (g/kWh),
- the designed service speed of the ship in knots,
- the total auxiliary engine kW size and
- the specific fuel consumption of the auxiliary engines (g/kWh).

Based on this set of variables the fuel consumption and “as derived result” the CO_2 emissions can be calculated.

Using the fleet structure and the emission-determining variables, a data sheet for 2010 as a base year and for 2015 as a first projection has been prepared. Table A.1 and A.2, shows the detailed specifications for respectively 2010 and 2015.

The standard fleet segments are identified as follows:
- CONT: Container
- DB_1_BC: Dry bulk / Bulk Carrier
- Gas_LNG_LPG Liquid gas carrier
- GC Gas Carrier
- GC_REEFER Gas Carrier Temperature conditioned
- LB_CH Liquid Bulk Chemicals
- LB_CR Liquid Bulk Crude
- LB_PROD Liquid Bulk Products

Table A.1: Data set on fleet segments and emission-determining variables for base year 2010

Type	Average_kW_Main_MOD	Average_SFOC_Main_MOD	Average_SPEE_SERV	Average_kW_Aux_Tot_MOD	Average_SFOC_Aux_MOD
CONT_1_PPAN_up60	56.661	171,3	24,9	10.920	204,6
CONT_2_PANA_60	32.121	172,9	23,1	6.577	208,3
CONT_3_SPAN_40	21.363	172,7	21,5	5.861	216,5
CONT_4_HAND_30	13.040	173,8	19,3	3.684	215,3
CONT_5_FEEM_15	7.039	180,9	17,0	1.459	227,2
CONT_6_FEED_5	2.366	196,3	13,4	648	230,0
DB_1_BC_CAPE_up_120	16.127	172,6	14,4	2.662	220,7
DB_2_BC_CAPE_85_120	12.038	172,8	14,3	2.541	220,9
DB_3_BC_PANA_60_85	10.060	175,1	14,3	1.917	228,0
DB_4_BC_HANM_35_60	8.427	176,2	14,3	2.061	225,7
DB_5_BC_HAND_15_35	6.507	182,6	14,1	1.526	228,1
DB_6_BC_COSTAL_0_15	2.152	194,9	12,1	530	230,0
GAS_LNG_LPG	10.025	184,1	15,2	6.116	208,9
GC_1_up15	8.132	182,3	15,2	2.335	236,9
GC_2_5_15	3.748	190,6	13,5	922	229,2
GC_3_to_5	1.143	200,6	11,2	290	235,4
GC_REEFER	5.400	190,5	16,3	3.779	223,3
GC_RORO_1_up15	14.734	174,7	19,7	4.488	226,3
GC_RORO_2_0_15	6.017	191,5	15,4	1.571	224,4
LB_CH_1_up_40	9.677	170,1	14,8	3.100	208,3
LB_CH_2_15_40	7.766	174,9	14,7	2.353	241,0
LB_CH_3_0_15	2.622	188,3	12,6	1.283	228,1
LB_CR_1_TK_ULCC	28.031	166,5	15,6	3.922	207,5
LB_CR_2_TK_VLCC	20.286	170,5	15,2	3.262	214,6
LB_CR_3_TK_SUEZ	13.301	170,6	14,8	2.598	222,0
LB_CR_4_TK_AFRA	12.070	174,0	14,6	2.235	228,8
LB_CR_5_TK_PANA	9.960	177,4	14,4	2.610	197,8
LB_CR_6_TK_HAND	3.955	196,6	12,9	627	230,0
LB_PROD	3.776	193,9	12,4		

The first projection of the specifications for 2015 is shown in the table A.2 below.

Table A.2: Data set on fleet segments and emission-determining variables for a 2015 projection

Type	Average_kW_Main_MOD	Average_SFOC_Main_MOD	Average_SPEE_SERV	Average_kW_Aux_Tot_MOD	Average_SFOC_Aux_MOD
CONT_1_PPAN_up60	56.566	171,8	24,5	11.503	203,7
CONT_2_PANA_60	33.663	172,1	23,2	6.792	207,7
CONT_3_SPAN_40	21.754	171,3	21,7	5.865	215,4
CONT_4_HAND_30	13.391	172,3	19,5	3.919	214,6
CONT_5_FEEM_15	7.187	179,4	17,1	1.618	226,5
CONT_6_FEED_5	2.519	195,1	13,4	606	230,0
DB_1_BC_CAPE_up_120	18.137	171,9	14,7	2.898	217,7
DB_2_BC_CAPE_85_120	12.735	173,0	14,4	2.529	224,5
DB_3_BC_PANA_60_85	10.453	172,5	14,3	1.926	223,1
DB_4_BC_HANM_35_60	8.732	173,7	14,2	2.029	223,6
DB_5_BC_HAND_15_35	6.287	176,7	13,9	1.766	226,1
DB_6_BC_COSTAL_0_15	1.983	191,8	11,8	539	230,0
GAS_LNG_LPG	10.745	183,1	15,4	5.241	210,4
GC_1_up15	8.456	174,9	15,1	2.352	219,7
GC_2_5_15	3.582	185,4	13,2	924	228,3
GC_3_to_5	1.135	197,9	11,2	306	229,9
GC_REEFER	5.157	188,8	16,0	3.694	222,9
GC_RORO_1_up15	15.129	171,8	19,8	4.711	208,3
GC_RORO_2_0_15	6.136	187,8	15,4	1.821	221,9
LB_CH_1_up_40	9.790	169,1	14,7	3.204	198,9
LB_CH_2_15_40	7.587	173,9	14,6	2.321	218,0
LB_CH_3_0_15	2.709	186,1	12,7	1.294	227,7
LB_CR_1_TK_ULCC	28.555	169,4	15,7	3.970	202,1
LB_CR_2_TK_VLCC	20.374	171,1	15,3	3.154	212,0
LB_CR_3_TK_SUEZ	13.462	171,1	14,9	2.589	219,4
LB_CR_4_TK_AFRA	12.487	172,3	14,7	2.298	227,5
LB_CR_5_TK_PANA	10.281	172,4	14,6	2.610	197,8
LB_CR_6_TK_HAND	2.805	197,0	12,2	1.103	230,0
LB_PROD	4.043	189,7	12,4		

For the projection of the years 2020, 2025 and 2030 the number of vessel per year is required. This information will come from the MOVEET model. Based on this information the projection for these three representative years will be prepared in a next step (task 2).

Special fleet segments

The following four segments, i.e. ferry, cruise, yachts and off-shore supply are to be considered somehow as special fleets due to regional fixedness (ferry and cruise

and off-shore supply) and their use independently from economical view points (yachts). Therefore, these segments need to be described here in more detail to understand their specific characteristics and the approach for the projection of these segments.
The projection for the above explained variables have been already made for the first three segments and are presented individually per ship segment and per variable. The specifications for the off-shore supply segment, still needs to be made.

Ferry fleet
Ferries are typical ships for regional European traffic in the Baltic Sea, North Sea, across the English Channel, in the Irish Sea, the western and eastern Mediterranean Sea and Black Sea. Most of them are engaged around Europe, smaller figures in Japan, China or Canada where similar geographical conditions exist. Routes are normally not longer than 24 hours, i.e. ferries are not found in transoceanic traffic. Usually they stay in the region for which they have been built, except they are sold after a certain period for further use elsewhere, especially from Japan to Indonesia or to Greece.

Prove for the European dominance in the market is that in Europe operate:
- The 10 or more largest ferries by GT
- The 10 or more largest ferries by number of beds
- The 10 or more largest ferries by number of lane meters (cargo capacity).

Table A.3: Survey on ferry types and sizes

Type*	Description	Remarks
Ferry	Pure passenger ship without cabins for short routes	Coastal traffic
Passenger ship	Pure passenger ship with cabins for overnight routes	Seldom/outdated
Passenger ferry	Pure passenger ship with cabins and deck places	Seldom/outdated
Passenger-ro/ro	Often called “Car ferry” for passengers and cars/trucks (commercial vehicles) in coastal and regional traffic	a wide-spread type
Railway ferry	Car ferry or ro/ro ship with rails for railway wagons and passenger facilities	Decreasing number; mostly included in car ferries
Ro/Pax	Car Ferry with high truck and trailer capacity	Increasing share
Cruise ferry	Car Ferry with cruise ship standard and minor vehicle capacity	Mostly in N. Europe - about 30 world-wide
Fast ferry	Ferry with higher speed than average, about 25 to 30 knots – see high-speed ferry	no clearly defined technical term
High-speed ferry	Fast ferry or car ferry constructed according to the high-speed code	In protected waters and warmer climates like the Med Sea

*) according to Lloyd’s Register

The study will mainly deal with “car ferries”. It is proposed to select four types for further steps of the study because of the limited total number:

1. Large size Ro/Pax (car ferries)

In northern Europe there are close to 50 large car ferries above 30,000 gt which include several cruise ferries. The largest size class has an average size of 40,000 gt while the maximum is 75,156 gt. In southern Europe the number is about 42 (see tables in following sub chapter).
The large ferries operate mostly on longer routes like:

Northern Europe:

- Stockholm – Helsinki / Turku
- Helsinki – Tallinn
- Copenhagen – Oslo
- Kiel – Oslo
- Kiel - Gothenburg
- Amsterdam – Newcastle
- Rotterdam – Hull / Harwich

Southern Europe:

- Barcelona - Italy
- Marseilles/Toulon – Corsica
- Marseilles – North Africa
- Genoa – Sardinia / Sicily
- Genoa - Tunis
- Venice – Patras

The number of large car ferries in Europe is not changing in a magnitude worth mentioning. The route network was established decades ago and the routes as well as the operators are consolidated now. New routes are seldom and can lead to the closure of others. If demand is increasing the ships operated on a specific route are replaced by larger ships, mostly without changing the number of ships. The abolishment of tax free sales in 1999 and the competition of low fare airlines have stopped the growth of ferry passenger transport. The current economic crisis has stopped the expansion of ro/ro transport in northern and southern European waters. Consequently, the number of large ferries, especially of cruise ferries, can hardly increase. A few will be constructed in the years to come, but in the 2020s others are nearing the end of their career.

The installed power depends on the speed the ferry needs to accomplish the regular trips in a certain time in the aim to offer the clients an attractive time-table. This may vary between 18 and 27 knots on most routes. Large ships are generally faster than smaller ones. In the Baltic Sea the ice conditions ask for high power. Consequently, the speed will not change in future and power demand only by better hull designs in a very distant future.

The speed of **large ferries** will not change in a large extend. Now the average speed is 23.7 knots. Should new ships be a little slower, e.g. 22 knots, they will replace the older ones which have an average speed of 22 knots. Only speeds of less than 22 knots will lead to a decrease of the average speed to less than 23.7 knots.

2. Medium-size passenger-ro/ro-ferry (car ferry)

The car ferry fleet consists of about 1.850 ships world-wide. Contrary to cargo vessels which often use flags of convenience, ferries are still often registered under the flag of the owner and the region of employment. The following figures show that this approach is very plausible.

- 595 ferries are operating in the Asia-Pacific region
- **450 ferries are operating in North European waters**
- **490 ferries are operating in the Med Sea / Black Sea region**
- 150 ferries are operating around North America
- 45 ferries are operating in Latin America
- 120 ferries are operating in remaining and undisclosed regions

Table A.4: Car ferries in Northern Europe according to size and flags

GT:	up to 1,000	1,000-4,999	5,000- 9,999	10,000-19,999	20,000-29,999	30,000+	Total
UK	28	19	8	3	8	12	78
Norway	93	94	13	2	-	4	206
Sweden	8	1	-	4	5	8	26
Denmark	18	17	-	9	1	6	51
Finland	10	2	-	1	-	7	20
Estonia	2	4	3	-	-	5	14
Germany	4	13	-	3	1	2	23
Netherlands	2	8	1	1	-	2	14
Latvia	1	-	-	1	-	3	5
Lithuania	1	-	-	-	2	-	3
Poland	9	-	-	-	-	-	9
North.Eur.	**176**	**158**	**25**	**24**	**17**	**49**	**449**

Source: ISL 2014 based Clarkson

The majority of the roughly 450 car ferries in Northern Europe has less than 5,000 gt. Ferries below 300 gt are generally excluded. More than 200 are operating under the Norwegian flag and thereof probably all under 5,000 gt on Norwegian inland routes. It is similar in the UK, Denmark and Germany where the smaller ferries are linking islands with the mainland. Thus, the number of ferries crossing the Baltic Sea, North Sea or Irish Sea is hardly more than 100 altogether.
The (world-wide) average size of the ferries <1,000 gt is 600 gt and 2.400 gt in the 1,000 to 5,000 gt size group.

The installed power depends on the speed the ferry needs to accomplish the regular trips in a certain time in the aim to offer the clients an attractive time table. This may vary between 14 and 20 knots on most routes. Consequently, the speed will not change in future and power demand only by better hull designs in a very distant future. Additional to ‘better hull design’, also better propeller and other measures that influences needed power.

Table A.5: Car ferries in Southern Europe according to size and flags

GT:	up to 1,000	1,000-4,999	5,000- 9,999	10,000-19,999	20,000-29,999	30,000+	Total
Italy	39	53	13	10	25	19	159
Greece	40	39	10	12	11	2	114
France	11	8	2	3	8	10	42
Spain	1	6	2	7	6	3	25
Zyprus	-	2	1	8	-	4	15
Malta	2	3	1	1	2	2	11
Morocco	-	-	3	7	2	-	12
Turkey	6	33	1	3	-	-	43
Croatia	16	19	4	1	-	-	40
Tunesia	3	-	-	-	-	2	5
Algeria	-	-	-	-	3	-	3
Russia	5	1	4	1	-	-	11
Portugal	1	-	2	-	-	-	3
Ukraine	4	2	-	-	-	-	6
Moldavia	-	1	-	-	-	-	1
Monte N.	1	-	-	-	-	-	1
Med Sea	**129**	**167**	**43**	**53**	**57**	**42**	**491**

Source: ISL 2014 based Clarkson

Similar to the northern countries most car ferries in the Med Sea are operated in coastal areas, especially around Italy and in the Aegean Sea. It is possible to define three route categories:

- Short routes in coastal waters like Naples – Ischia, Piraeus – Aegina or Dalmatian islands
- Medium routes to larger islands like Barcelona – Balearic Islands, Italy - Sardinia or Piraeus – Crete
- Long routes across the Med Sea like Marseilles – Algeria, Genoa – Tunis or Venice – Greece.

The size classes below 1,000 gt mostly fit to the local routes, medium size ships serve the big island routes and the largest ones typically the long routes.
For the further analysis medium size means the 449 + 491 ferries in Europe excluding the largest category (49 + 42) and the smallest (176 + 129), adding up to 544 medium sized ferries. Their number will only change marginally because of the consolidated route network. A reduction is expected at the lower end – the smallest and slowest ferries – which are often in danger of replacement by bridges.
The speed is calculated based on the world fleet. The medium size ferries (1,025) have an average speed of 17.7 knots. The newbuildings of the latest years show a slightly increased speed of 18.2 knots. Since the speed of ferries is not expected to increase because of the relation to existing routes, the increase of the average is possible if some of the smallest ferries are replaced by bridges.

3. High-speed passenger ferry:

The most reliable source of information for such ships is ShipPax of Sweden who are publishing yearly updates, e.g. the pocket booklet ShipPax HISpeed. The statistics show that the number of high-speed ferries is 1,682 in total including 168 car ferries (2013). The total number has not changed between August 2011 and August 2013.
The most important subtype is the catamaran (953) followed by hydrofoils (322) and Monohulls (299). SES (surface effect ships) and hovercraft play only minor roles. The shares of hydrofoils and SES are decreasing and the share of monohulls is increasing.

Table A.6: High-speed ferries (passenger only) mainly consist of following types

Type	**No. 2011**	**Aver.y.o.b.**	**Aver. GT**	**Aver. Pax**	**No. 2013**
Catamaran	953	1996	836	314	953
Hydrofoil	325	1981	154	135	322
Hovercraft	30	1986	66	115	30
Monohull	299	1994	641	265	304
SES	75	1986	342	185	73
Total	**1,682**				**1,682**

Source: ShipPax: HiSpeed 11, 13

Fast Ferry International has published order and delivery numbers which prove the construction of 30 to 60 new ships per year, most of them in the 100 to 200 seat size.

Table A.7: High-speed ferry (passenger only) deliveries by year and capacity

Pax capac.	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	Total
50 to 99	1	6	11	6	2	8	10	8	9	4	14	6	85
100 to 199	12	12	23	12	20	11	18	22	10	8	9	10	167
200 to 299	2	5	11	14	5	7	8	9	5	11	11	8	96
300 to 399	9	8	4	3	4	5	6	3	1	6	2	2	53
> 400	4	6	10	9	6	2	2	8	11	4	8	5	75
Total	28	37	59	44	37	33	44	50	36	33	44	31	476
Source: Fast Ferry International 2001 to 2012													

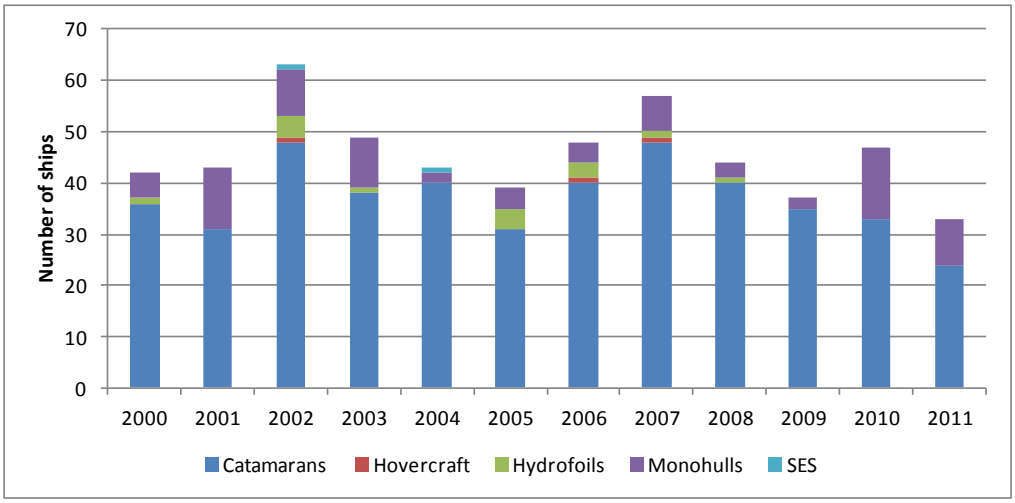
Such small ferries typically operate on short routes in protected waters like Hong Kong – Macao, in Norwegian Fjords or like mentioned above (short routes in coastal waters like Naples – Ischia, Piraeus – Aegina or Dalmatian islands). Their size is often below 300 gt but the high speed of 30, 40 or more kts. requires much power, e.g. two high-speed MTU or Cat diesel engines of 2,000 kW.

Table A.8: Leading European operators of passenger only high-speed ferries

Operator	Region	Number 2011	Main type	Typical pax	Number 2013
Alilauro	Italy	17	F,C,M	150 – 400	17
Aliscafi	Italy	14	C,F	150 – 300	7
Atlas	Croatia	7	F	155 – 400	7
Boreal	Norway	9	C	90 – 250	10
Caremar	Italy	5	F	210 – 240	3
Fjord1	Norway	11	C	70 - 295	7
Hellenic Seaways	Greece	15	F, C	132 - 438	13
Istanbul Deniz	Turkey	28	C	350 – 449	28
Jadrolinja	Croatia	8	C	306 – 335	8
Navigazione Libera	Italy	12	M	250 – 450	12
Siremar	Italy	13	F	124 – 240	14
Tide Sjö / Norled	Norway	18	C	130 – 250	20
Torghatten	Norway	8	C	130 – 214	8
Ustica Lines	Italy	25	F,C,M	210 – 312	25
Total		**190**			**179**

Source: ISL 2014 based on ShipPax

Among the subtypes catamarans clearly dominate, followed by monohulls.



Source: ISL 2014 based on Fast Ferry International

Figure A.1: High-speed ship deliveries by year and type

The same total fleet number of 1,682 in 2011 and 2013 and the more or less stagnating number of deliveries indicate that the fleet is no more increasing. The average age is the reason to assume that further newbuildings are needed to replace ships sold for scrap.

The problem with these high speed passenger ferries is that the main source of information doesn't allow to calculating the real total figures and average speed because ShipPax has set a lower entrance limit for the register at 25 knots deliberately omitting an unknown figure of vessels**.**

4. High-speed car ferry:

Because of the definition problem no exact figures of high-speed ferries are available. Based on information given by "Fast Ferry International" and ShipPax the number is approximately 150 world-wide. The following table shows a yearly production average of 5 ships per year.

Table A.9: High-speed car ferry deliveries 2000 to 2011 by car capacity

Car capac.	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011
5 to 49	2	1	2	1	2	3	2	2	3	-	2	1
50 to 149	3	-	-	3	3	1	1	-	2	2	-	-
150 to 249	4	4	-	-	1	1	1	3	2	-	1	-
250 to 349	5	-	2	1	-	1	-	1	-	1	-	-
350 to 500	-	1	-	-	-	-	-	1	1	1	-	1
Total	14	6	4	5	6	6	4	7	8	4	3	2
Source: Fast Ferry International 2001 to 2012												

High-speed car ferries have been operated in the northern European waters, but not very successfully because of the often too rough seas and high operating costs. Also in the Mediterranean Sea the number is now negligible.
A short analysis of the world high-speed fleet based on the Clarkson fleet data base shows that out of 135 "fast passenger car ferries" approximately

- 14 are large car ferries (between 20 and 30 kts.) but not high-speed ferries
- 17 are operating in North European waters (Norway, Denmark, Gotland)
- 47 are operating in the Med Sea / Black Sea region (Balearic Islands, Canary Islands, Gibraltar, Aegean Sea, Dardanelles)
- 27 are operating in the Asia-Pacific region
- 13 are operating in Latin America
- 17 are operating in undisclosed regions.

One world-wide basis the average speed of 99 high-speed car ferries could be evaluated. It is 38 knots. A real difference between the older and younger vessels is not discernible. Therefore, a major change is not expected in future.
The average power of high speed car ferries is 25,500 kW currently. It is expected to increase because older HS ferries will be replaced by larger ones.

Summary of ferry figures

Table A.10: Development of car ferry numbers in Europe

	2010	2013	2015	2020	2025	2030	Region
Large car ferries	84	92	92	94	96	98	Europe
Medium car ferries	550	544	540	530	520	510	Europe
High-speed car f.	66	64	63	62	61	60	Europe

The deadweight figure seems to be not very useful because of the different subtypes of ferries with low to high cargo capacity. The dwt figure reaches from less than 20 % to more than 100 % of the gt figure. A low percentage means that it is mainly used for fuel/ballast and supplies.

Table A.11: Development of the average main engine power of car ferries

	2010	2013	2015	2020	2025	2030	Region
Large car ferries	34000	34,300	34500	35000	35000	35000	World
Medium car ferries	8800	8900	9000	10000	10500	10800	World
High-speed car f.	25000	25500	26000	26500	27000	27500	World

Source: ISL 2014

It is expected that the power will decrease by better hull designs, but these savings will be balanced by an increasing ship size.

Table A.12: Development of the average auxiliary engine power of car ferries (estimation)

	2010	2013	2015	2020	2025	2030	Region
Large car ferries	5230	5277	5307	5384	5384	5384	World
Medium car ferries	1354	1369	1384	1538	1615	1661	World
High-speed car f.	3846	3923	4000	4077	4153	4230	World

A broad analysis of register data is not useful because of the very small share of filled-in data fields.

Table A.13: Development of the average maximum speed of car ferries

	2010	2013	2015	2020	2025	2030	Region
Large car ferries	25.5	25.5	25.5	25.5	25.3	24.8	World
Medium car ferries	19.4	19.5	19.6	19.8	19.8	19.8	World
High-speed car f.	40.5	40.5	40.5	40.5	40.5	40.5	World

Table A.14: Development of the average service speed of car ferries

	2010	2013	2015	2020	2025	2030	Region
Large car ferries	23.7	23.7	23.7	23.7	23.5	23	World
Medium car ferries	17.6	17.7	17.8	18	18	18	World
High-speed car f.	38	38	38	38	38	38	World

Selected Car Ferries

Table A.15: Selected Car Ferries

Vessel name (No. of same design)	Y.o.B.	GT	tdw	Main kW	Type	Aux. kW	Type	Trial speed	Serv. speed
TANIT	2012	52,645	6,126	4x 14,400	MAN 12V48/60CR	4x 3,000	MAN 6L32/40	28.6	27.5
PIANA	2011	42,180	7,569	4x 9,600	Wä 8L46CR	3x 1,520	Wä 8L20	27.6	23.9
STENA SUPERFAST VII	2000	30,285	5,915	4x 11,500	Sulzer 12ZAV40S	3x 1,848	MAN 8L28/32H		25
BLUE STAR DELOS	2011	18,498	2,300	4x 8,000	MAN 16V32/40	3x 1320	MAN 6L21/31		26
EDOYFJORD	2012	1,632	304	2x746	Cat C32 ACERT	2 x 150	Cat C9 DITA	14	13
LOLLAND	2012	4,500	949	5x 874	Cat C32-RNX	-	-	16	12

SFOC in g/kWH

Table A.16: Specific Fuel Oil Consumption

Make/Type	Main engine	auxiliary
MAN 48/60	180	
MAN 32/40	181	183
MAN 28/32		188
MAN 21/31		184
Wärtsilä 46C	173	
Wärtsilä 20		186
Cat C32 ACERT	203	
Cat C9		220

Cruise fleet

The cruise fleet needs a different way of looking at the things, not only because of a different size and age structure, mainly because of a different seasonally changing movement pattern. Cruise shipping is a part of the tourism industry not of sea transport. The result is that much more ships navigate in European waters during the summer, but winter deployment is also increasing. Cruise shipping is more or less short sea shipping with daily port visits, i.e. round trips with port calls during the day and nights at sea. A typical seven night cruise consists of two days at sea (24 h steaming) and five days with port visits including the turnaround port (12 h steaming and 8h in port each). This means 40 h in port per week and 128 h at sea inclusive manoeuvring. For longer cruises the share of port stays per week is similar. Speed may vary between the individual voyage sections between the ports. A high share of energy is not required for propulsion but for lighting, air conditioning etc.
The ISL has prepared a list of cruise vessels which is now called “Ocean cruise fleet” for more than 30 years. It includes the vessels of different types engaged in cruise shipping excluding cruise vessels in long-term lay-up. The definition regards a lower size of 1,000 gt (formerly grt) and 100 beds, the so-called lower beds, normally two in a cabin. A recent analysis of the fleet of small cruise ships (40 to 99 beds) confirms that these can be neglected for the aim of this study: Out of a total of 85 “coastal cruisers” only 15 are operating in European waters, especially in Greece and Croatia, and these are very small (around 500 gt).
The Ocean cruise fleet increased from around 150 vessels 30 years ago to nearly 300 vessels actually. Three decades before the structure of this fleet was much more heterogeneous. The share of purpose-built cruise vessels has been quite small while liner vessels had still a strong presence. These served their liner duties during the summer and offered pleasure trips outside the liner season in warmer waters like the Caribbean Sea. Smaller vessels went out of service during the winter. The fleet included also car ferries surplus to requirements in Northern Europe during the winter. It still includes a few icebreakers used for polar cruises. Modern cruise ships in numbers worth mentioning are being built since 40 years. A few of them were sold recently for scrap, a few more are still in service. They are the best benchmark for determining the economic lifespan of cruise ships which is 40 years. This long period is due to the high investment cost and good care during the lifespan.

Cruise vessels can be split into several subtypes:

- Mass market vessels up to 5,400 lower beds
- Luxury vessels of small to medium size
- Expedition ships of small size

The mass market vessels are often used for round trips repeated all over the year or throughout the season, typically seven nights long but ranging from one to 14 nights.

Luxury vessels offer individually planned routes, not only roundtrips but also offered as sections of longer routes up to round-the-world trips.
Expedition ships visit extreme locations far from beaten tracks, e.g. Arctic and Antarctic regions, remote islands or tropical paradises. The latter can be neglected in this study.

A further special feature of cruise shipping is that there is no demand to carry passengers like cargo from the port of origin to the port of destination – that would be liner or ferry shipping. The development of guest carryings in cruise shipping is driven by the supply of capacity in certain regions. Cruise ship owners and operators provide the ships and organize the trips and passengers decide to choose which ship and which route they want to book. And they are free in their decision where to go or not to make a cruise at all. This has been the basis of the development of cruise shipping and will be the basis for further growth of the industry.

The analysts agree that “demand” will continue to grow and the number of guests will double at least. The worldwide long-term development is based on three main phases and source markets:

- The North American market
- The European market
- The Asian market

Neglecting modest earlier developments in Germany, the UK or Greece, the first major source market for cruises was the North American market attracted by cruise offers in the Caribbean Sea (since early 1970s) and other destinations around the Continent. It dominates the cruising world until now with around 12 mill. passengers per year which book most of the trips from American ports.

Source markets no 2 and 3 are the UK and Germany with much smaller numbers. Europe in total has only passed the 6 mill. mark but is now showing a much faster growth rate. Until 2030 the European market is expected to double. The stagnation in 2012 is explained by the weak economy in South European countries which are expected to recover within a few years. Further growth will come by a general higher market penetration and from smaller source markets which are not yet targeted specifically.

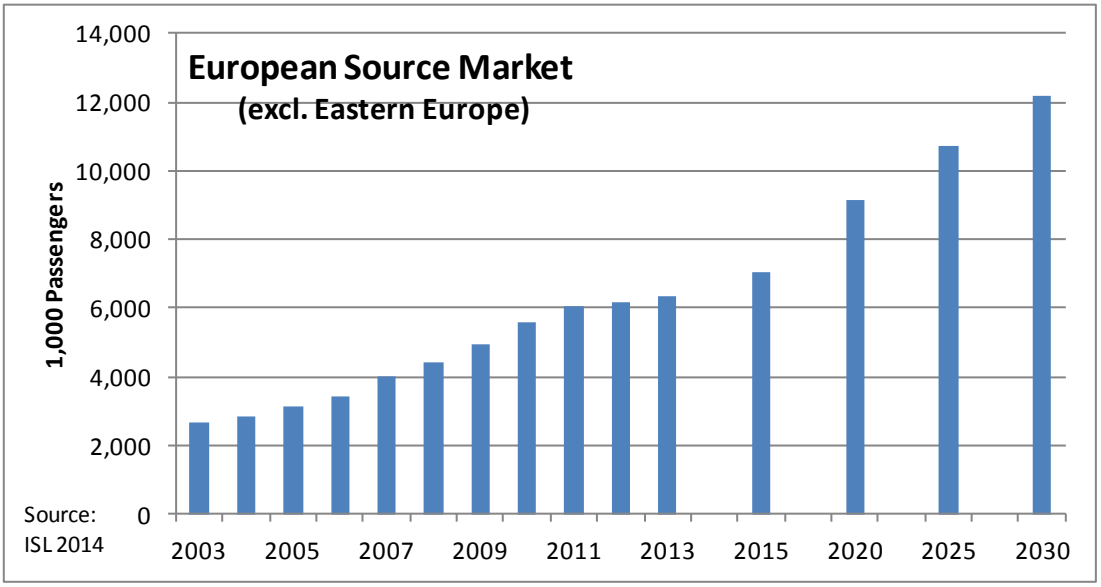


Figure A.2: Development of passenger numbers

Not so much is left for the balance to the total of around 22 mill. pax world-wide. However, since the Chinese have started to make pleasure cruises recently, the Europeans will be overtaken by Asian passengers in a not too distant future.

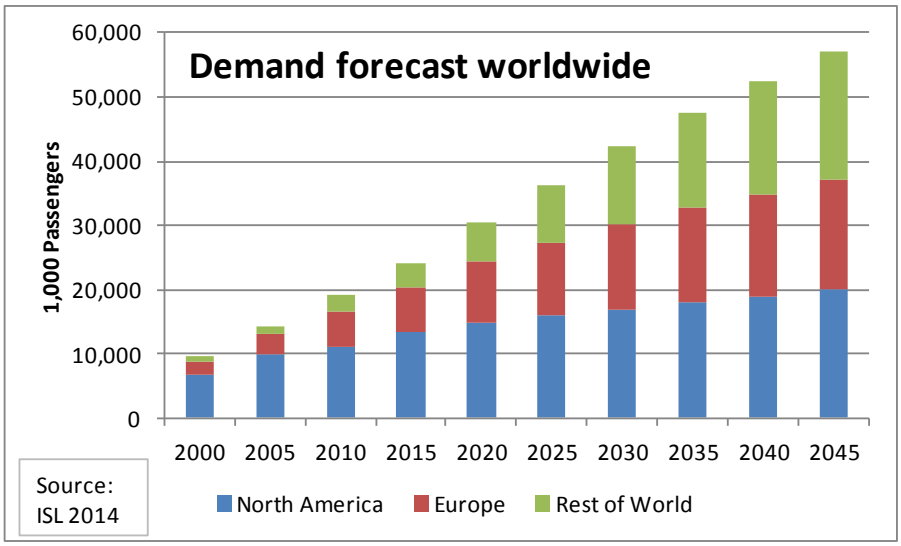


Figure A.3: Demand forecast worldwide

Number of ships:

Under consideration of past developments, operator's strategies, newbuilding capacities etc., the fleet capacity is expected to grow to 850,000 beds by 2030. Other than the nearly doubling of capacity the number of ships will only grow slightly to about 370 vessels.

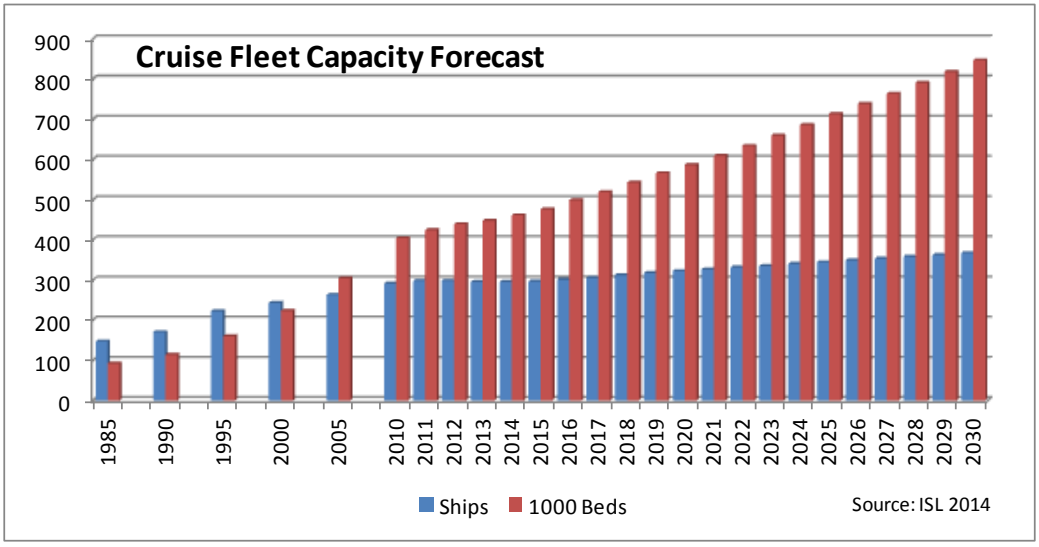


Figure A.4: Cruise fleet capacity forecast

The reason for the modest increase of the number of ships is the enduring growth of the individual ships. In 1983 the average size of the cruise ships had been 15,000 grt and by 2013 it reached nearly 60,000 gt, four times the size of 30 years

ago. And this growth will go on because smaller ships will be replaced by larger ones and the size of the largest new ships is also still increasing. For a few years the number of cruise ships will stagnate just below 300 because the number of ships to be withdrawn is similar to the number of new ships. To continue the actual yearly increase rate of the ocean cruise fleet of 20,000 beds p.a. exactly five vessels of 4,000 beds are sufficient, and this is the usual capacity of recent newbuildings. Between 2015 and 2020 the number of withdrawn vessels will go back due to the lack of deliveries in the late 1970s. After 2020 the number of new vessels is expected to be higher than sales for scrap.

By 2010 the number of cruise ships permanently or partly engaged in European waters has been 155 of 291. It will stay at about 155 until 2020 and increase slightly to 165 by 2030.

Based on the fleet of 2010 and the expected fleet of 2020 (new additions to the fleet are known until 2016) the fleet could be grouped into size classes and corresponding estimations were made for the years until 2030.

Finally, for each size group the fleet expected to operate in European waters in 2010, 2015, 2020, 2025 and 2030 could be defined and one particular ship type representing the size groups was selected.

A further step in the calculation of emissions is the estimation of the presence of these ship types in the European cruising regions. The total of 100 % includes periods outside Europe, because many ships are not permanently in Europe.

Speed:
The average speed of the Ocean Cruise Fleet is currently exactly 20 knots. Some older and all the small ships are slower but large new ships are faster than 20 knots. The average speed will increase until 2020 because many slower vessels will leave the fleet and mainly larger ships will be added. A stagnation around 20.5 knots is expected between 2020 and 2015 because newbuildings have to save energy and emissions and a slightly lower speed helps to reach this aim. Finally, these slower new ships can reduce the average speed back to 20 knots.
The expected variation is nearly negligible and will be more than compensated by changes in cruise itineraries. Other routes, lower numbers of ports or longer port stays are expected to reduce the time at sea and the speed on the individual legs of a cruise trip.

Energy generation:
Diesel engines and diesel-electric plants are the typical configurations in the engine rooms of cruise vessels. One ship, an icebreaker, is fitted with a nuclear reactor and one hat a steam turbine by 2013. The last-mentioned was sold for scrap meanwhile. Between 2001 and 2006 a total of 17 vessels were fitted with a combination of gas turbines and diesel engines. This era seems to be terminated but the ships will survive until 2030.
Older passenger vessels are driven by one or two 2-stroke diesels. The latest one came into service in 1990 and, therefore, their share will decrease from 7 % to 2 % until 2025 and zero by 2030. More important are the 100 ships (34 %) with 4-stroke diesel engines. Such are pure diesel configuration was installed until 2010 and cannot be excluded in future for smaller ships.

Most widespread is the diesel-electric configuration with several diesel generators for general energy generation, a switchboard and the consumers like electric motors for the propellers, air conditioning, light, kitchen etc. The diesel engines are always running at optimal speed, but, depending on energy demand, not all at the same time. Such a diesel-electric plant is currently the optimal system and the share is expected to increase to about 80 %. Combined with gas as fuel no better alternative is available.

Table A.17: Share of engine configurations in cruise vessels

Configuration	2012	2013	2015	2020	2025	2030
diesel-electric	52	53	55	66	73	81
4-stroke diesel	34	34	33	25	20	14
2-stroke diesel	8	7	6	4	2	0
others	6	6	6	5	5	5
Total in %	100	100	100	100	100	100
Ships in fleet	291	295	296	322	344	367

Source: ISL 2014

The average power (kW) in cruise vessels is difficult to demonstrate because the ships have to be grouped according to the engine configurations. Due to the small total number this is not justified. Since more than 50 % of the fleet has diesel-electric systems this should be assumed as normal case. In future the average power will develop in two directions:

- In the group of smaller ships the average power will increase because many of the smallest vessels will leave the fleet and only a small number of somewhat larger ships will be added.
- No change is expected in the middle size group. There is a smaller number of deletions and additions and the trend to larger ships is balanced by energy saving methods.
- In the upper size group no ships will be deleted and all the new ships will need much less energy per gt than the older vessels even if they are somewhat larger.

Selected ship designs for 3 size classes

Table A.18: Introd……

Vessel name (No. of same design)	Y.o.B.	GT	tdw	Main kW	Type	Aux.	Trial speed	knots
CELBRITY SOLSTICE (5)	2008	121,878	9,500	67,200	16V46C	-	25,0	24,0
MSC FANTASIA (4)	2008	137,936	15,000	71,400	12V46	-	23,3 max	22,3
AIDAdiva (7)	2007	69,203	8,811	36,000	9M43C	-	23,0	19,5
MARINA (2)	2011	66,084	6,000	42,000	12V46C	-	21,7	19,5
R1 to R8 (8)	1999	30,277	2,700	19,440	12V32D	-		18,0
SILVER SPIRIT	2009	36,009	3,882	26,000	9L38B	-		20,3

All motors are designed by Wärtsilä except the AIDAdiva which has Caterpillar MaK engines.
The SFOC of the type 46 is 175 g/kWh, type 38 is 174 g/kWh and MaK 9M43 is 175.

Summary of cruise figures

Table A.19: Number of cruise vessels in Europe (cruise season)

GT Year:	2010	2013	2015	2020	2025	2030
>100,000 gt	19	27	27	33	41	50
50,000 – 100,000 gt	41	48	48	55	60	65
<50,000 gt	95	90	80	67	59	50

The deadweight figure seems to be not relevant because cruise vessels don't carry cargo. If necessary, it is about 10 % of the gt figure.

Table A.20: Average kW installed in main engines or diesel-electric systems by size group

	2010	2013	2015	2020	2025	2030
> 100,000 gt	71,380	70,500	70,400	70,000	68,000	66,000
50-100,000 gt	52,600	52,560	52,500	52,400	52,200	52,000
< 50,000 gt	14,900	15,260	15,500	16,160	16,420	18,320
Ships in fleet	291	297	296	322	344	367

Source: ISL 2014

Auxiliary engines
More than 50 % of the existing vessels and nearly all newbuildings don't have auxiliary engines because of the diesel-electric design.

Max speed of cruise vessels
Maximum speed data are not available generally. For examples see table with selected vessels.

Table A.21: Design speed of cruise vessels (the effective operating speed is often lower)

GT Year:	2010	2013*	2015	2020	2025	2030
>100,000 gt	22.1	22.2	22.3	22.5	22.3	22.1
50,000 – 100,000 gt	21.7	21.8	21.9	22.0	22.2	22.0
<50,000 gt	17.8	17.9	18.0	18.3	18.6	19.0
Average all sizes	19.8	20.0	20.1	20.4	20.7	21.0

*) calculated, other figures estimated

Private yachts
The yacht fleet needs a different way of looking at the things, also different from cruise vessels. Yachts are private ships with no need to earn money (except charter yachts) and have more extended times in port.
Yacht is a not very well defined ship type ranging from smallest boats to the 180 m private “Giga Yacht” AZZAM. There are mainly motor yachts but also respectable sailing yachts. The latter can be ignored for this study. There are also some sub-types of private yachts like “explorer yachts”, displacement or planing designs etc. which cannot be analyzed separately.
Most yachts are owned and used privately but an increasing share is owned by companies (operators) for charter trips. The size of charter yachts may be similar to private yachts and coastal cruisers but the number of beds is lower. In the available statistics it is impossible to separate charter yachts from private ones.
By most sources the yachts are not grouped by capacity or tonnage but just by length. The number of units decreases with increasing length groups. For the purpose of this study a minimum length of 30 m is proposed due to the existing sources of information. The main difference to cruise vessels is that some yachts are designed as fast ships but probably all yachts are not regularly at sea. Most of their time they are moored in their home port (marina) or at a shipyard for maintenance.

The yacht fleet is increasing very fast worldwide. A lot of shipyards entered the scene while Europe is still the leading region for yacht construction.

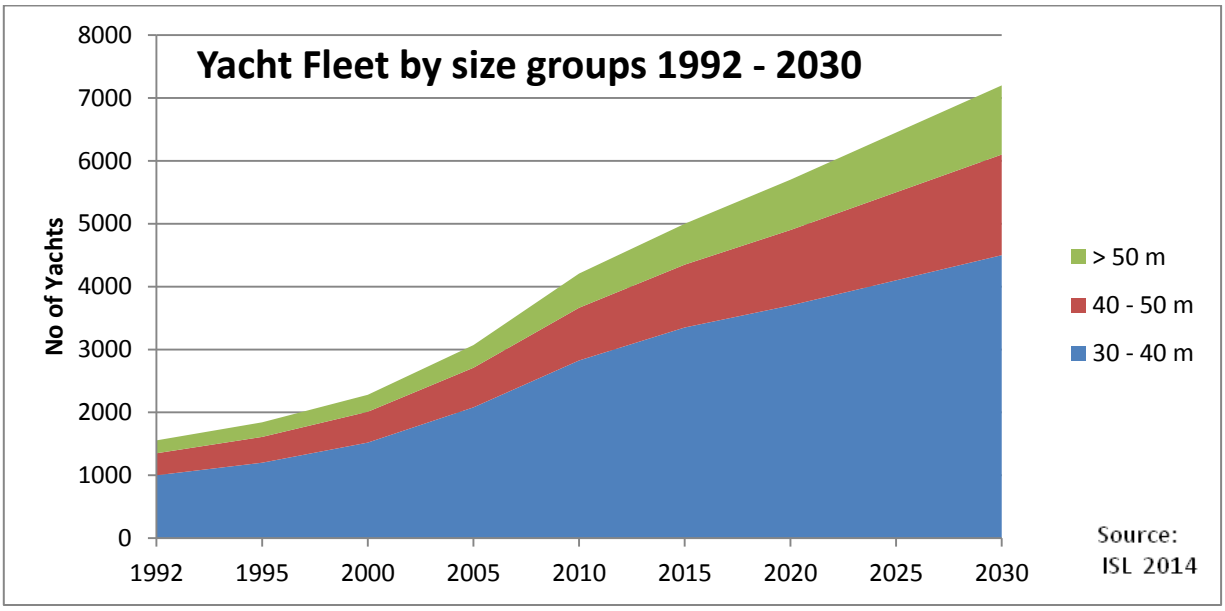


Figure A.5: Yacht fleet by size groups 1992 -2030

By 2010 the fleet included:

2,826 yachts	of 30 - 40 m
838 yachts	of 40 - 50 m
544 yachts	of more than 50 up 180 m

The total number is expected by the yachting industry to rise from 4,200 to 7,200 by 2030. Currently the growth is weaker than between 2005 and 2010, but the number of contracts at the shipyards is rising again. The ordering activity had been affected more severely by the financial crises in the “smaller” size class of 30 – 40 m than in the larger size classes.

Table A.22: Shipyard order book for “Super Yachts” >50m:

Year	New orders	Deliveries	Order book
2007	..		106
2008	..		144
2009	24		152
2010	23		136
2011	37		126
2012	30		131
2013	23	35	110
2014	-		116

Source: ISL 2014 based on “The Superyacht” February 2014 and others

The order book for yachts > 50 m reached a peak of around 150 at the beginning of the financial crisis which affected ordering activities heavily. After a low of 110 by 2013 the business is, probably, recovering currently.

About 25 % of the 4,200 yachts are sailing yachts which should be neglected regarding GHG emissions. Since in the order book the share of sailing yachts is only 15 % their share of the total fleet will decrease.

The “Golden Triangle” of the world cruising scene is the western Mediterranean Sea between St. Tropez, Mallorca and Corsica. In 2010 two thirds of the world yacht fleet was located there and more than 80 % had been in the Med Sea. In the following years the figure has been somewhat lower at 72 %. The situation changes in winter when many yacht owners prefer warmer climates. Than the Med has a share of only 32 % or even less.

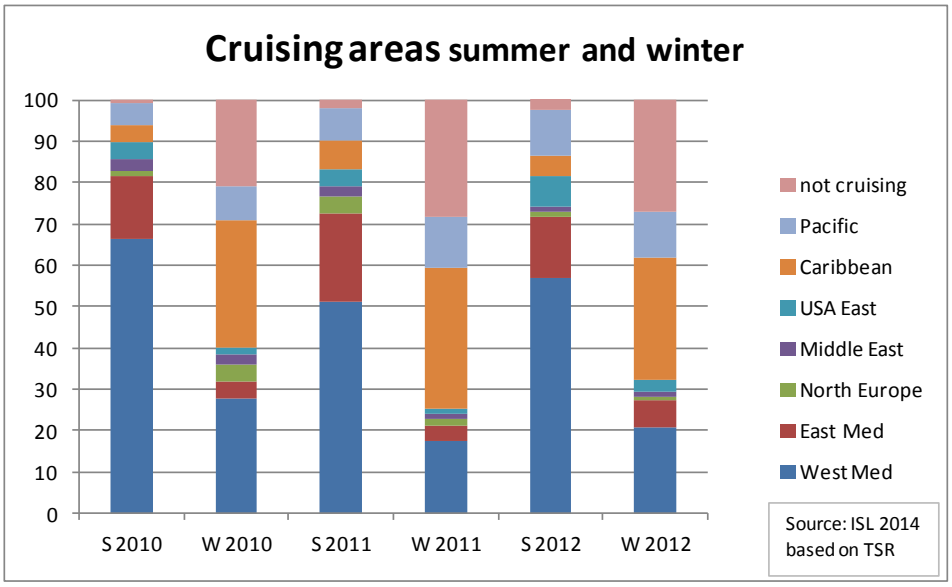


Figure A.6: Cruising areas

The regional distribution is underlined by the nationality of the yacht owners. Most of them are Europeans, especially if Turks and Russians are included.

Table A.23:Yacht ownership:

Region	thereof
55% Europe	Turkey 9 %, Germany 5%, Italy 2%, Switzerland 2%
15 % the Americas	USA 10 %, Mexico 3%, Canada 2%
30 % Rest of world	Russia 14%, Australia 4%, China 3%, Japan 2%

Source: ISL 2014 based on “The Superyacht” February 2014

The seasonal relocation of the yachts is not only a matter of steaming longer distances on own keel; meanwhile there are some heavy lift shipping companies which found a lucrative niche in carrying yachts across the Atlantic either loaded by crane or by flow-in/flow-out in dock ships.

An important fact regarding the emissions is that yachts are moored in port most of the time and that they can use the port’s electricity network. The following graph gives an indication of the time in port and in shipyards. It remains to be proved where they spend the remaining time and what means “private use”. Does it mean time under power or also at anchor etc.?

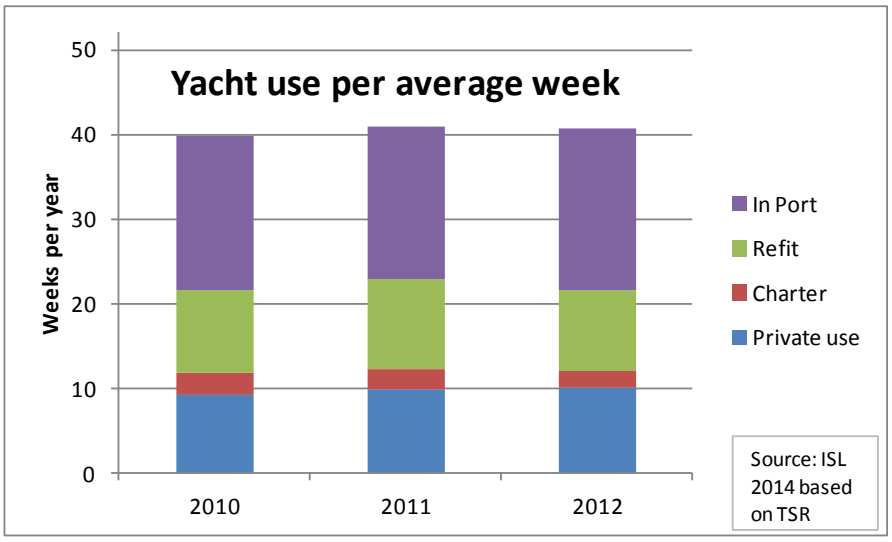


Figure A.7: Yacht use per average week

No statistics about the speed are readily available. A special analysis of the largest yachts of the world No. 51 to 100 (length between 74 m and 85 m) shows that the average installed power in main engines is 4,840 kW. However, the range is between 3,000 (excluding historic ships with less powerful engines) and 12,000 kW. The power depends just on the decision of the owner. Even less is known about auxiliaries but this seems to be less important because yachts are often in the port where they can use land-side power. The majority of the yachts is much smaller and, therefore, an average power of 2x 750 kW is assumed. Trends are not known and cannot be based on economic reasons in case of yacht owners.

Table A.24: Summary yacht figures world-wide:

	2010	2013	2015	2020	2025	2030
No of yachts < 30 m	4,200	4,600	5,000	5,700	6,450	7,200
Thereof motor yachts	3,150	3,450	3,800	4,400	5,050	5,700
Deadweight``	-	-	-	-	-	-
Av. main power in kW*	3,000	3,000	3,000	3,000	3,000	3,000
Av. auxil. power in kW**	200	200	200	200	200	200
Max speed in knots°	23.7	23.7	23.7	23.7	23.7	23.7
Cruise speed in knots	20.2	20.2	20.2	20.2	20.2	20.2
SFOC MTU 4000 M70	223	223	223	223	223	223
SFOC Cat 3512B DITA	208	208	208	208	208	208

``) not relevant, mainly used for fuel and drinking water

*) main power above 3,000 kW in small yachts (30-40m) and below 3,000 in larger yachts (50-75m) because larger yachts have lower speed

**) less than 100 kW in yachts of 30-40m and 500 kW in yachts >50m. Attention: yachts use land-side power supply in marinas

°) the maximum speed may be much higher than the cruise speed, e.g. if a gas turbine is installed in addition to diesel engines

Regarding the engines used in yachts, there is one preferred brand for all size classes: MTU. In the 40- 70 m size class previously Caterpillar was dominating but since 2012 MTU has a share of more than 50 % also here. (Source: The Superyacht Report No 149). The sfoc of a typical yacht motor (MTU 8V 2000 M72) is 196 g/kW at optimum and 207 g/kW at rated power.

About 75 % of these yachts are in Europe in summer and 30 % during the winter.

Based on the data on the defined variables per fleet segment, the modelling of the emissions will be performed.

B Reference vessels

For each of the vessel types as defined in paragraph 3.7 ‘The Reference Vessels; some reference vessels have been identified by looking through maritime databases such as Fairplay’s Internet ship Register and Grosstonnage.com (Fairplay) (grosstonnage.com). These reference vessels were built in the last 5 years, or have recently been launched and are to be taken in service soon.

Table B.1: The reference vessels

IMO	Year built	Name	Type	Notes	GT	DWT	Service speed	# Main engines	Main engine power	RPM	Propellers	Thrusters	Draught	Loa	Lpp	Bm	Depth
9599078	2013	AM LIBERIA	dry bulk		51905	98730	14,5	1	12700	99	FPSS	none	14.479	240.000	236.000	38.000	19.950
9641376	2013	SHOYOH	dry bulk		60876	97144	14,2	1	9680	90	FPSS	none	13.056	239.900	234.500	43.000	20.500
9599200	2014	GL IGUAZU	dry bulk		51905	98704	14,5	1	10820	94	FPSS	none	14.479	139.990	236.000	38.000	19.950
9618721	2014	ANATOY SIDENKO	general cargo		5686	7240	11,5	2	1200	1000	FPTS	FPFT	4.700	139.950	133.680	16.500	6.000
9694701	2013	INTAN DAYA 32	general cargo		6075	7000	11,4	2	1545	525	FPTS	none	6.000	99.800	93.000	22.000	9.000
9561007	2013	OCEAN 01	general cargo		4425	7200	10	1	2648	240	FPSS	none	6.900	107.280	98.500	16.800	9.100
9679555	2014	CCNI IQUIQUE	container		70262	80087	19	1	31640	80	FPSS	n/a	13.000	270.900	258.400	42.800	24.600
9475648	2011	MOL MANEUVER	container		78312	79423	24,5	1	57200	102	FPSS	tunnelFT	14.232	301.970	288.000	43.400	20.140
9660011	2013	YM MOVEMENT	container		71821	73370	15	1	53000	90	FPSS	tunnelFT	14.021	293.180	176.000	40.000	24.300
9609964	2014	ARK DANIA	roro and vehicle	roro cargo	33313	12000	18,6	2	9080	146	CPTS	CPFT	7.000	195.000	185.000	30.500	10.800
9668506	2014	NEPTUNE THALASS	roro and vehicle	vehicles	37602	11262	19,4	1	11620	127	CPSS	+ tunnelAT	8.700	169.550	158.000	28.000	30.560
9687306	2014	WEDELLSBORG	roro and vehicle	roro cargo	23030	11630	18	2	5040	750	CPTS	CPFT	7.600	179.460	169.850	26.210	17.600
9452880	2011	AFRODITI	oil tanker +80 dwt crude		84716	166164	15,2	1	18660	91	FPSS	none	17.300	274.200	264.000	50.000	23.100
9607423	2012	EPHESOS	oil tanker +80 dwt crude		84850	164733	15,3	1	18660	91	FPSS	none	17.171	274.180	264.000	50.000	23.100
9461776	2011	GENMAR SPARTIAT	oil tanker +80 dwt crude		84723	164714	15,8	1	18660	91	FPSS	none	171.171	274.190	264.000	50.000	23.100
9394076	2015	DORADO	oil tanker -80 dwt product	product	7212	12365	10,6	1	3000	750	FPSS	none	7.000	149.350	143.150	17.300	10.200
9706944	2014	GLOBAL VENUS	oil tanker -80 dwt product	product + chemical	7494	12871	13,5	1	4200	170	FPSS	n/a	8.715	127.680	119.800	19.600	11.550
9621663	2012	XIN MING DA 28	oil tanker -80 dwt product	product	8344	12637	12,5	1	3552	600	FPSS	none	8.200	131.600	123.000	20.800	11.200
9622069	2013	ABLE SAILOR	chemicals	chemical + product	20563	29745	14,5	1	6480	136	FPSS	none	9.500	177.210	168.000	29.000	14.400
9617650	2015	JO LARIX	chemicals	chemical + product	20500	30000	14,8	1	8280	129	FPSS	none	10.000	184.000	n/a	28.400	15.200
9733674	2015	MINAMINIPPON O	chemicals	chemical tanker	21100	30000	n/a	1	14280	105	FPSS	n/a	10.000	175.000	166.700	27.700	16.000

Figure B.1: AM Liberia dry bulk vessel. Image from (Marine Traffic)

Figure B.2: SHOYOH dry bulk vessel. Image from (Marine Traffic)

Figure B.3: GL IGUAZU dry bulk vessel. Image from (Ship Spotting)

Figure B.4: ANATOLIY SIDENKO general cargo vessek. Image from (Marine Traffic)

Figure B.5: INTAN DAYA general cargo vessel. Image from (Marine Traffic)

Figure B.6: MOL MANEUVER container vessel. Image from (Marine Traffic)

Figure B.7: YM MOVEMENT container vessel. Image from (Marine Traffic)

Figure B.8: ARK DANIA roro cargo vessel. Image from (Marine Traffic)

Figure B.9: NEPTUNE TALASSA vehicle carrier. Image from (Marine Traffic)

Figure B.10: WEDELLSBORG roro vessel. Image from (Marine Traffic)

Figure B.11: AFRODITTI crude oil tanker Image from (Marine Traffic)

Figure B.12: EPHESOS crude oil tanker. Image from (Marine Traffic)

Figure B.13: GENMAR SPARTIATE crude oil tanker. Image from (Ship Spotting)

Figure B.14: GLOBAL VENUS product and chemical tanker. Image from (Vessel Finder)

Figure B.15: ABLE SAILOR chemical and product tanker. Image from (Marine Traffic)

C Data for the maritime market model

Table C.1 below shows the yearly output (in ton per nautical mile), fixed costs (in euros), and variable costs (in euros per nautical miles).

Table C.1: Yearly output (in ton per nautical mile), fixed costs (in euros), and variable costs (in euros per nautical miles).

	Output (freight rate) (ton.nm)	Fixed costs (€)	Variable costs (fuel costs)(€/ton.nm)
Dry Bulk	2,963,136,000	5,250,000	0.00076
General Cargo	132,581,000	1,875,000	0.00283
Container 4000 TEU	2,956,325,000	10,500,000	0.00253
Reefer	193,925,000	2,250,000	0.00569
RoRo & vehicle	356,400,000	3,000,000	0.00436
OilTanker-mainly crude > 80' dwt	5,931,341,000	11,250,000	0.00065
OilTankers-mainly product < 80'dwt	223,344,000	3,600,000	0.00154
Chemicals	697,702,000	4,200,000	0.00182
LNG & LPG	1,566,576,000	4,500,000	0.00155
RoPax	53,158,000	7,500,000	0.03312

After implementation of technical or operational measures, variable and fixed costs change. The change in variable and fixed costs per vessel-type per scenario is given in Table C.2. Variable costs changes are given in euro per ton per nautical mile. Fixed cost changes are given in euros annually in the table C.2 below.

Table C.2: The change in variable and fixed cost per vessel type per scenario.

		No regret	Zero cost	Maximal abatement
Dry bulk	Change in fixed costs	500,037	1,360,316	1,360,316
	Change in variable costs	-0.0003927	-0.0004480	-0.0004480
General Cargo	Change in fixed costs	6,694	40,833	545,221
	Change in variable costs	-0.0004956	-0.0006457	-0.0012687
Container 4000 TEU	Change in fixed costs	683,619	2,086,668	2,086,668
	Change in variable costs	-0.0005959	-0.0007566	-0.0007566
Reefer	Change in fixed costs	53,552	245,299	625,348
	Change in variable costs	-0.0007261	-0.0013342	-0.0016967
RoRo & vehicle	Change in fixed costs	222,239	677,474	911,762
	Change in variable costs	-0.0015827	-0.0019208	-0.0020061
OilTanker-mainly crude > 80' dwt	Change in fixed costs	805,616	1,640,024	1,640,024
	Change in variable costs	-0.0003194	-0.0003595	-0.0003595
OilTankers-mainly product < 80'dwt	Change in fixed costs	6,694	42,507	583,676
	Change in variable costs	-0.0003497	-0.0004261	-0.0007567
Chemicals	Change in fixed costs	278,468	542,544	542,544
	Change in variable costs	-0.0007392	-0.0008206	-0.0008206
LNG & LPG	Change in fixed costs	79,658	623,875	918,408
	Change in variable costs	-0.0001992	-0.0004256	-0.0004649
RoPax	Change in fixed costs	217,787	442,034	921,488
	Change in variable costs	-0.0056518	-0.0083986	-0.0098602

Table below (Table C.3) gives the assumed shares in maritime shipping per vessel type. The price for transportation by rail or road is obtained by calculating the weighted price for rail/ road, where price for transportation by rail is €0.003941685 per ton per Nautical mile and price for transportation by road is €0.031533 per ton per nautical mile (Crisalli, Comi, and Rosati 2013)[9].

Table C.3: The assumed shares in maritime shipping per vessel type.

	Price (in €) for transportation by rail/road	Share of transportation by maritime shipping	Share of transportation by rail/road
Dry bulk	0.019708423	90.00%	10.00%
General Cargo	0.025836196	60.00%	40.00%
Container 4000 TEU	0.025836196	60.00%	40.00%
Reefer	0.025836196	30.00%	70.00%
RoRo & vehicle	0.028742649	20.00%	80.00%
OilTanker-mainly crude > 80' dwt	0.019708423	95.00%	5.00%
OilTankers-mainly product < 80'dwt	0.019708423	80.00%	20.00%
Chemicals	0.022738593	80.00%	20.00%
LNG & LPG	0.019708423	90.00%	10.00%
RoPax	0.017737581	10.00%	90.00%

[9] Crisalli, Umberto, Antonio Comi, and Luca Rosati. 2013. "A Methodology for the Assessment of Rail-Road Freight Transport Policies." *Procedia - Social and Behavioral Sciences* 87: 292–305