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The Potential Contribution of the Shipping Sector to an Efficient Reduction of Global Carbon Dioxide Emissions *

Nadine Heitmann and Sonja Peterson

In this paper, we analyze how much the shipping sector could contribute to global CO_2 emission reductions from an efficiency point of view. To do this, a marginal abatement cost curve (MACC) for the shipping sector is generated that can be combined with a MACC for conventional CO_2 abatement in the production and consumption sectors around the world. These two MACCs are used to assess the following as regards the various global reduction targets: (a) what the maximum global cost savings would be that could be achieved by abating emissions in the shipping sector, (b) how much the shipping sector could contribute to abating emissions cost efficiently, and (c) what the potential additional costs of implementing a separate solution for the shipping sector would be. The focus is on the year 2020. We find that the shipping sector could always contribute to efficient global emission reductions and thus could always achieve global cost savings, but also that the size of the contribution and the size of cost savings depend heavily on the MACC case assumed, i.e., on how the existence of negative abatement costs is treated in a MACC, and on the reduction potentials and costs of measures assumed.

Keywords: climate change, shipping sector, CO_2 emissions, marginal abatement cost curve

JEL classification: Q52, Q54, Q58

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1 Introduction

The Second IMO GHG Study 2009 (Buhaug et al., 2009) of the International Maritime Organization (IMO) on greenhouse gases (GHG) in the shipping sector presented two important insights. First, the shipping sector contributed about 3.3% to global GHG emissions in 2007, which is more than what was assumed before.[1] Second, the shipping sector's CO_2 emissions are projected to increase significantly in the coming decades if its emissions remain unregulated (Buhaug et al., 2009). The consequence would be that in the next decades the shipping sector's CO_2 emissions would constitute a considerable proportion of the maximum allowed emissions, i.e., the maximum emissions that are in line with the United Nations Framework Convention on Climate Change's (UNFCCC) 2°C target (UNEP, 2011). Thus, other sectors would have to emit less and reduce their emissions further to offset the increase in shipping emissions.

This has led to discussions on how to regulate the shipping sector's CO_2 emissions, discussions which are continuing not only in the IMO, but also in the scientific community. These discussions center around the question whether this sector should be subject to an emission cap or whether it should be subject to some other means of reducing emissions (UNEP, 2011). Progress was made when the IMO agreed on two mandatory efficiency measures to reduce CO_2 emissions from shipping in July 2011, (MEPC, 2011): the Energy Efficiency Design Index (EEDI), which is exclusively for newly built ships, and the Ship Energy Efficiency Management Plan (SEEMP). Market-based policies for the shipping sector are also being discussed and investigated (MEPC, 2010).

While there is some literature on the pros and cons of different allocation options to allocate shipping emissions to countries and on their effects for specific country groups (den Elzen et al., 2007, Gilbert and Bows, 2012, Heitmann und Khalilian, 2011, Wang, 2010) and some literature on technical abatement potentials and the costs of different measures (Buhaug et al., 2009, Eide et al. 2011, 2009, Faber et al., 2011a/Wang et al., 2010,[2] Faber et al., 2009, Longva et al., 2010), the literature on how much the shipping sector should contribute to global emission reductions from an efficiency point of view remains limited. Only Eide et al.

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[1] In addition, the shipping sector was one of the world's major CO_2 emitters in 2007 (evidenced by comparing CO_2 emissions of shipping in 2007 (Buhaug et al., 2009) with data on CO_2 emissions from fuel combustion per country in 2007 (IEA, 2009b).

[2] Note that Faber et al. (2011a) is an updated version of Wang et al. (2010), but that only the later provides data that we make use of in this paper.

(2009) derive a decision criterion for regulating CO_2 emissions in the shipping sector that is in line with the 2°C target. Yet, the importance of regulating CO_2 emissions in the shipping sector can only be assessed, when the potential cost savings are known. Also, how CO_2 emissions should be regulated depends on what the efficient contribution of the shipping sector actually is. In this paper, we thus want to address these issues.

From a methodological point of view, the problem is that global top-down economy-climate models or integrated assessment models (IAMs) that are able to analyze the cost efficient contributions of various sectors do not or do not explicitly include the shipping sector. Another approach, which is less sophisticated and simpler, to include the shipping sector is using marginal abatement cost curves (MACCs) (see Criqui et al., 1999, Ellerman and Decaux, 1998). This approach is mostly used to analyze the impacts of international emissions trading at the country level (see, e.g., Ellerman and Decaux, 1998, den Elzen et al., 2005, Löschel and Zhang, 2002, Rickels et al., 2012), but can also be used to calculate sectoral contributions to emission reductions. While using MACCs has some drawbacks and results have to be treated with care (Kesicki and Ekins, 2012, Kesicki and Strachan, 2011, Klepper and Peterson, 2006, Morris et al., forth.), MACCs can nevertheless provide an indication of the cost effective contributions of various nations/sectors to emission reductions.

The information on abatement costs and potentials that is available for the shipping sector is a few expert-based MACC studies that have been published recently (Buhaug et al. 2009, Eide et al. 2011, Faber et al. 2011a/Wang et al. 2010, and Faber et al., 2009). We use this information to generate a global MACC for the shipping sector that can be combined with a MACC for conventional CO_2 abatement in the production and consumption sectors around the world. We then use these two MACCs to assess for various global reduction targets: (a) the maximum global cost savings that could be achieved by emission abatement in the shipping sector, (b) the cost efficient abatement contributions of the shipping sector to the global reduction targets, and (c) the potential additional costs that would be incurred by implementing a separate solution for the shipping sector. We focus on the year 2020.

This paper is structured as follows. Section 2 provides some background information on the shipping sector, gives an overview of existing MACC studies, and discusses the methodological challenges that arise when using an expert-based cost assessment in combination with MACCs generated by a top-down model. The main challenge is how to treat the negative abatement costs that are found in the MACC studies of the shipping sector. We discuss how these negative abatement costs can be interpreted and suggest three different approaches to deal with them in our context. Accordingly, we derive three different MACCs and corresponding marginal abatement cost functions for the shipping sector. Section 3 shows how the computable general equilibrium (CGE) model DART (Dynamic Applied Regional Trade) can be used to generate a global MACC, excluding the shipping sector, and a corresponding marginal abatement cost function. Section 4 describes three global emission reduction scenarios and presents the model results for these scenarios, in particular, the efficient contribution of the shipping sector and the global cost savings. Section 5 discusses the results and Section 6 summarizes and concludes.

2 Generating a MACC for the shipping sector

2.1 Overview of MACC studies

Faber et al. (2011b) provide a comparative analysis of recently published MACC studies for the world fleet. Overall, four major expert-based MACC studies exist that estimate the maximum reduction potential of abatement measures, which are mainly energy-efficiency measures, and their respective abatement costs for the world fleet (or a specific share of it) for the years 2010, 2020, and 2030 (Buhaug et al. 2009, Eide et al., 2011, Faber et al., 2011a/Wang et al., 2010, and Faber et al., 2009). Table 1 presents an overview of the assumptions made in these studies and results for the year 2020, the year we focus on in our analysis.[3]

Table 1: Overview of expert-based MACCs: assumptions and results

Study	Year	Base year	Baseline emissions (Mt CO_2)	Maximum abatement potential (Mt CO_2)	Cost effective potential <0$/t (Mt CO_2)	Measures included	Measures applied to	Fuel price ($/t)	Discount rate (in %)
Buhaug et al. (2009)	2020	2007	1250	210-440	135-365	25 grouped into 10	fleet average	500 (1,000, 1,500)	4 (16)
Eide et al. (2011)	2020	2008	1191	487	290	25	59 ship segments	350 (HFO) 500 (MDO) 350-450 (LNG)	5
Faber et al. (2011a)	2020	2007	[a]~1290	436	340	22 grouped into 15	53 ship segments	700, 900	10 (4 and 18)

[a] In Faber et al. (2011a), the baseline is not given explicitly (central estimate 436 Mt are 33% of the baseline in 2020 and 340 Mt are 26% of the baseline in 2020).

Source: Own presentation based on Buhaug et al. (2009), Eide et al. (2011), and Faber et al (2011a).

The MACC estimates shown in Table 1 have in common that the maximum abatement potential of the world fleet is large (about 15% – 40% relative to business-as-usual (BAU)

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[3] Faber et al. (2009) present a MACC for the year 2030 that is not included in Table 1.

emissions) and that an important share of the maximum abatement potential could be achieved at negative costs. This cost-effective abatement potential is, without any further regulation being required, in the order of between 255 Mt CO_2[4] and 340 Mt CO_2 for 2020 (Eide et al., 2011, Faber et al., 2011a/Wang et al., 2010), or between 20%–26% of projected emissions in 2020.

Data is often not available on the costs and abatement potentials of abatement measures. Therefore, the MACC studies include only measures for which costs and abatement potential estimates exist (e.g., Faber et al., 2011a/Wang et al., 2010). Some measures may be mutually exclusive, which also has to be taken into account when generating the abatement cost curves from these data (Faber et al., 2011a). This fact also allows the generated curves to be interpreted as MACCs, which they are not in the narrower sense, since they only calculate the average cost per ton abated and not of the marginal (last) ton abated.

The MACC studies often differentiate between several categories of abatement measures, which differ from each other in terms of, e.g., costs and implementation, see Table 2. For example, Faber et al. (2011a)/Wang et al. (2010) differentiate between operational and technical measures, whereas Eide et al. (2011) differentiate between operational and technical measures, alternative fuels and/or power sources, and structural changes.

Table 2: Categories of measure types

	Operational measures	Technical measures	Alternative fuels/power sources	Structural changes
Purpose	operartion and maintenannce of ships	reduction of power requirement to engines or improving energy-efficiency	alternative set of technical measures	include energy-efficiency improvemnts in interaction between two counterparts in shipping
Examples	enhanced weather routing, hull and propeller cleaning, slow steaming	lower energy consumption in main and auxiliary engines, optimised hulls	LNG, wind power, solar panels	improved charter contracts, enhanced logistics and fleet planning
Costs	low investment costs, moderate operating costs	high investment costs, moderate operating costs,	high investment costs	
Emissions reduction potential	low	high	high	high
Implementation	in general all ships	often limited to new ships	[a]lack of infrastructure (supply and size of storage tanks on bord), still R&D status, or only for niche market	in general hard to develop and implement

[a] Faber et al. (2011a)

Source: Own presentation based on Eide et al. (2011) and Faber et al. (2011a).

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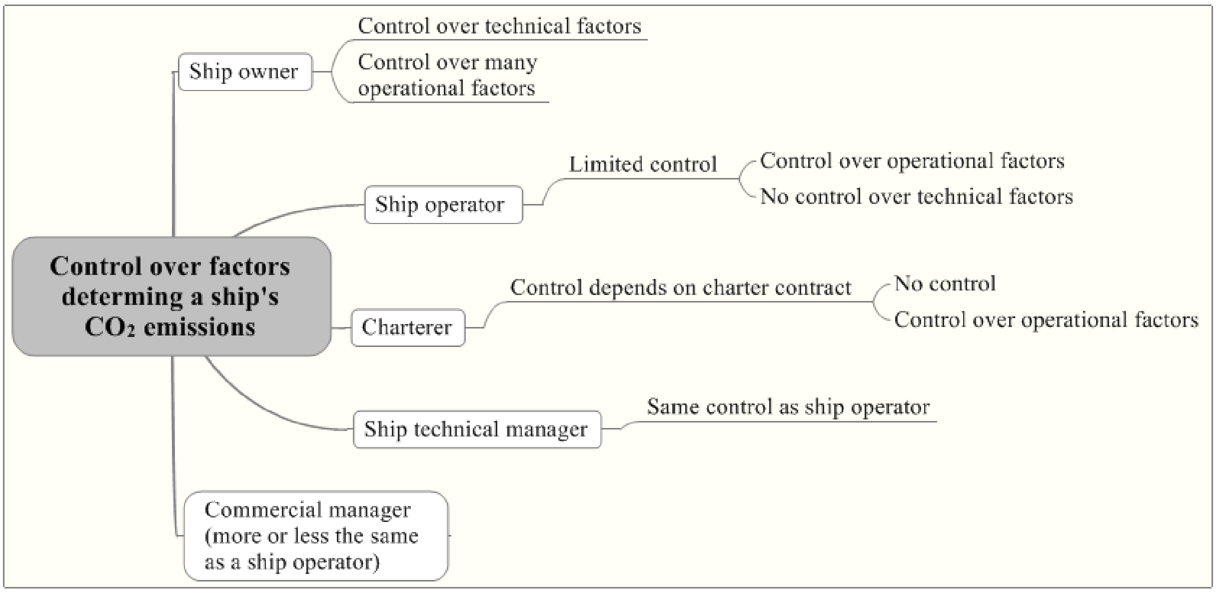
[4] This number represents the central estimate of cost-effective potential (<0$/t) in Buhaug et al. (2009).

Operational measures mainly concern the operation and maintenance of ships and are characterized by low investment and moderate operating costs, and low abatement potential. An example for such a measure is the implementation of a system that improves routing, i.e., to avoid unfavorable conditions that cause unnecessary fuel consumption. The measure reduces fuel costs and CO_2 emissions, but incurs investment costs to buy and implement the system and it incurs operating costs to maintain and manage the system. Technical measures mainly concern technical design features of ships and are characterized by high investment and moderate operating costs. An example for such a measure is the implementation of a waste heat recovery system that can be used to generate electricity alternatively to auxiliary engines and thus reduce fuel consumption (Faber et al., 2011a/Wang et al., 2010). Structural changes mainly concern the improvement of common practice, e.g., charter contracts or port efficiency, with regard to energy efficiency. Alternative fuels/power sources mainly concern substitutes, e.g., liquefied natural gas for motive power, for the use of carbon-intensive fuels. Both categories of measure types are characterized by high abatement potential, but at the same time are limited in application, e.g., because there is a lack of mature infrastructure for liquefied natural gas, or are difficult to develop (Eide et al., 2011, Faber et al., 2011a).

Finally, it is important to keep in mind that multiple actors in the shipping sector control the factors that determine a ship's CO_2 emissions, see Figure 1.

Figure 1: Actors in shipping and their control over factors determining a ship's CO_2 emissions



Source: Own presentation based on Faber et al. (2011a, 2010).

Ship owners have control over technical measures and many operational measures, whereas the other actors mainly have control over operational measures only. The owner can decide whether or not to implement technical measures, whereas the other actors cannot. Nevertheless, they might be able to decide whether or not to apply/implement operational measures, but this depends on the contract between the owner and the other actors (Faber et al., 2010). However, both technical and operational measures are mostly subject to the issue of split incentives (ICCT, 2011) and this distinction is crucial for constructing our own set of MACCs for the shipping sector and, in particular, for how we treat negative abatement costs.

2.2 Negative abatement costs

One problem with expert-based MACCs is the existence of negative abatement costs.[5] In contrast, MACCs generated by models (bottom-up partial-equilibrium models and top-down CGE models) by construction generate only positive abatement costs. The assumption in all models is that rational individuals implement abatement measures that have negative costs even in the absence of climate policy, whereas they implement abatement measures that have positive abatement costs only if climate policy gives rise to a price on CO_2 emissions. However, the question arises why such abatement measures (that have negative abatement costs), which often represent established, nonrisky technological or operational measures, are not embraced by the market participants. Various studies have tried to explain the existence of negative abatement costs in expert-based MACC estimates in general (IPCC, 2007, Kesicki and Ekins, 2012). Their main explanation is that expert-based MACCs are mostly based on a very narrow cost definition, namely project costs that ignore potential additional costs. The project costs are the costs of an individual abatement option that is assumed to have no significant indirect economic impacts on markets and prices. Of the potential additional costs that are ignored, those that stem from barriers to implementation are, in particular, important for the shipping sector. Several such barriers are presented in the shipping-specific literature (Eide et al., 2011, Faber et al., 2011a/Wang et al., 2010, ICCT, 2011). Faber et al. (2011b) find four important reasons for nonadoption of cost-effective measures: low priority of energy-efficiency improvements, split incentives[6] between the owner of a ship and a charterer, transaction costs to collect relevant information about energy-efficiency

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[5] See, e.g., the very popular abatement cost curves published by McKinsey (Enkvist et al., 2010).

[6] Jaffe and Stavins (1994) argue that if the actor who invests in an efficiency-improving measure is not the same actor as the actor who benefits, implementation is unlikely. Investment will occur only, if the investor gets the investment recovered by the beneficiary of the efficiency-improving measure. In case of the shipping sector, this issue concerns the relationship between the ship owner and the charterer.

improvement measures, and the possibility of time lags between the implementation of measures and the measures becoming cost-effective. Here, the issue of split incentives is that the ship owner bears the investment costs of an abatement measure (e.g., main engine retrofit), whereas the operator/charterer receives the benefits in terms of reductions in operating costs (e.g., less fuel consumption) (Faber et al., 2010). Eide et al. (2011) stress in particular that the issue of split incentives between ship owners and charterers can, to a certain degree, explain the nonadoption of cost-effective measures. Generally, Faber et al. (2011b) argue that the main barriers are of a technical, financial, and structural/institutional nature. Understanding the barriers to implementation is important in order to design effective regulation. Some barriers may be overcome by having price signals, whereas others may be overcome by enacting laws.

We follow Hyman et al. (2002) to deal with negative abatement costs in expert-based MACCs. They propose two approaches to approximate a function based on an underlying engineering estimate of marginal abatement costs.

The first approach is to assume that no-regret options, i.e., measures that reduce emissions at negative net costs (IPCC, 2001), are not economical when accounting for all relevant costs and to shift up the MACC so that it lies above the horizontal axis. The second approach is to assume that all no-regret options are undertaken, even in the absence of any climate policy. Thus, only the positive part of the MACC, i.e., the reduction potential at positive marginal abatement costs (MACs), is relevant. Here, the negative part of the MACC needs to be subtracted from the baseline emissions, where the reduction potentials of these measures, i.e., the measures that have negative abatement costs, are not taken into account yet. The first approach implicitly assumes that the barriers to implementation or extra cost are relevant for the implementation of all measures, also for the ones with positive abatement costs. Since it assumes that the level of the extra costs is exactly the level of the measure with the highest negative costs, it uses, in some sense, a lower bound estimate for the extra costs. It thus tends to overestimate the size of the contribution of the shipping sector to emission reductions. The second approach underestimates total global CO_2 emissions in the business-as-usual (BAU) or reference scenario without any emission reduction measures, since not all of the measures with negative abatement costs may actually be undertaken, and at the same time it underestimates the size of the contribution of the shipping sector to emission reductions, since some of the measures with negative abatement costs may be implemented only with the extra incentives of carbon prices. For this reason, we add a third approach to those of Hyman et al.

(2002) that deals with the issue of barriers to implementation. The third approach is to assume that measures are subject to barriers to implementation, in particular, to the issue of split incentives, which is an apparent phenomena in the shipping sector. We assume that the issue of barriers to implementation is more pronounced for some measures than for others because some of the measures are already employed by a significant proportion of the world fleet according to ICCT (2011).[7] We thus assume that all no-regrets measures for which the issue of barriers to implementation is less pronounced are undertaken, arguing that these would nevertheless be implemented by the actors who have control over such measures and at the same time bear the fuel costs. These measures are thus not considered in the MACC as is done in the second approach.[8] We further assume, when accounting for all relevant costs that all no-regret measures for which the issue of barriers to implementation is pronounced are assumed to be not economical. The MACC is thus shifted up, so that costs lie above the horizontal axis as in the first approach. This implies that costs associated with abatement measures that have positive abatement costs that are subject to the split incentives issue are also shifted up.

It is difficult to tell which of these approaches is most realistic. We clearly believe that there are barriers to implementation that have some kind of shadow price. Thus, we consider the first and third approaches to be realistic, whereas we consider the second approach to be rather academic. Although we acknowledge that shifting up the MACC by exactly the level of measure with the highest negative costs is an arbitrary choice, we nevertheless, consider the first approach to be best suited as our central case.

2.3 Generating MACCs and MAC functions

We follow the methodology presented in Eide et al. (2011) and Faber et al. (2011a)/Wang et al. (2010) in order to generate customized MACCs of the shipping sector. This methodology includes, in general, a projection of the fleet development, the determination of a business-as-usual (BAU) emissions scenario, i.e., determining the amount of CO_2 emissions that would be emitted if no abatement measures were taken in a given year, and the calculation of CO_2 reduction potential and corresponding costs per measure and ship for a given year.

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[7] This relates to the following measures: autopilot adjustment, water flow optimization, weather routing, hull cleaning, propeller polishing, and speed controlled pumps and fans.

[8] Faber et al. (2011b) argue that measures that are already employed by ships should be excluded from a MACC analysis. We assume that a correction of BAU emissions is not necessary when excluding such measures from the analysis because the pre-fuel consumption of a ship, i.e., the fuel consumption before measures are employed, is assumed to already include the reduction potential of such measures.

The MACC is obtained by ordering the costs in increasing order and then plotting them against their corresponding reduction potentials.

We assume that abatement efforts in the shipping sector start in 2020, i.e., ships first start to implement abatement measures from 2020 onwards. This assumption is based on the given condition that ships currently have no incentives, despite the two mandatory efficiency measures EEDI and SEEMP, to implement abatement measures.

Based on this assumption, we first project the world fleet composition in 2020 based on the current world fleet composition and ship-type-specific growth and scrapping rates. We use data from SeaWeb (IHS Fairplay, 2012) in order to determine the current world fleet composition, i.e., the number of ships per ship-type/ship-age category, whereby a ship type is subdivided into various ship segments.[9] These categories (subcategories) correspond to the categories in Buhaug et al. (2009), but since we work with data on abatement measures from Wang et al. (2010), the world fleet under consideration here consists of 14 major ship types that are divided into 53 size segments instead of 18 ship types and 70 segments, as in Buhaug et al. (2009).[10] We use ship-type specific growth and scrapping rates from Eide et al. (2011) in order to project the current fleet up to 2020. This means we first allocate ships of the current fleet into ship-segment/ship-age categories, which gives us the total number of ships per segment and the number per ship-segment/ship-age category. Then, we apply the growth and scrapping rates to the total number of ships in the ship segment. We add the number of new ships to the new age category, category 1, whereupon the former age category 1 becomes age category 2, and subtract the number of scrapped ships from the last age categories. As in Wang et al. (2010) the age category ranges from 1 to 30 years. For simplicity, we treat those few ships older than 30 years that we find in the current age distribution of the world fleet the same as 30-year-old ships. In other words, abatement measures only have an effective duration of one year when applied to such ships, thus, causing high abatement costs.

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[9] For example, the ship type crude oil tanker could be subdivided into various segments by deadweight (see Buhaug et al., 2009).

[10] The 14 ship types are the following: crude tanker, products tanker, chemical tanker, LPG tanker, LNG tanker, other tankers, bulker, general cargo, other dry general cargo, container, vehicle carrier, roro, ferry, and cruise ships. The term world fleet might be misleading because most noncargo ships (fishing boats, military ships, service ships, etc.) are not included. However, the 14 ship types include all major ship types that are predominantly cargo ships engaged in merchant shipping and noncargo ships like passenger ships. Thus, we use the term fleet instead of world fleet in the following.

We determine the baseline CO_2 emissions of the world fleet as projected to 2020 by following Eide et al. (2011) and Faber (2011a)/Wang et al. (2010), who assume the same operational profile as the 2007 fleet in Buhaug et al. (2009) for the projected fleet. The operational profile and the ship-type-specific characteristics (for more details, see Buhaug et al., 2009) determine the fuel consumption of a ship per year. Moreover, Eide et al. (2011) introduce a general improvement factor of 5% for ships built in 2010 and 8% for ships built in 2020, which mirrors the assumption that new-built ships are more energy efficient than older ships. Given this, we assume that the fuel consumption of ships built between 2008 and 2010 decreases by 1.64% per year compared to ships built before 2008 and that of ships built between 2011 and 2020 by 0.28% per year. To calculate the BAU emissions, we multiply the number of ships per ship-segment/ship-age category in 2020 by the pre-fuel consumption of a ship, i.e., its fuel consumption before abatement measures are implemented.

The data on abatement measures from Wang et al. (2010) include high and low estimates of recurring (investment) and annual nonrecurring (operating and maintenance) costs, and fuel reduction (and thus CO_2 emissions abatement[11]) potentials for 22 measures and 14 major ship types. In addition, an effective duration (in years) is assigned to each measure, e.g., a waste heat recovery system has an effective duration of 8 years, whereas a solar energy system an effective duration of 30 years (SNAME et al., 2010). Because some of the measures are mutually exclusive, they are grouped into 15 groups in order to avoid overestimating abatement potentials (Wang et al., 2010, ICCT, 2011).[12] Moreover, the individual reduction effects and corresponding CO_2 emission abatement achieved by all the measures that could be implemented simultaneously on a ship are calculated first and then ordered according to their abatement costs per ton of CO_2 (increasing order). The measure with the lowest abatement cost is selected and assumed to be applied first. Its emission reduction is calculated based on a ship's pre-installation fuel consumption and the individual reduction effect. Then, the individual reduction effects and abatement costs of all the remaining measures are recalculated. The fuel reduction potential of the second applied measure is calculated based

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[11] The assumed conversion factor is 3.13.

[12] The 15 groups consist of the following measures: operational speed reduction, weather routing, autopilot adjustment, propeller maintenance, hull cleaning, hull coating, optimization water flow of hull openings, air lubrication, propulsion upgrade, main engine adjustment, waste heat recovery, wind power, solar power, low energy lightning, and speed control of pumps and fans (see Faber et al. (2011a)/Wang et al. (2010) and ICCT (2011) for more details).

on the reduced fuel consumption resulting from the first applied measure (Eide et al., 2011 and Faber et al., 2011a/Wang et al., 2010).

We apply the same calculation approach as presented in Eide et al. (2009) and applied in Eide et al. (2011) to calculate abatement costs (in Eide et al., 2009, 2011 the costs are called CATCH, cost of averting a tonne of CO_2-eq heating,). The abatement costs (*AC*) of a measure are determined by the net present value of total costs (C_t) minus total benefits (B_t) of a measure, whereby *i* represents the discount rate, divided by the total CO_2 emission reduction potential (see Equation 1).

$$AC = \frac{\sum_{t=1}^{T} \frac{C_t - B_t}{(1+i)^{t-1}}}{T \cdot CO_2^{red}} \quad with\ t=1,\ldots,T. \tag{1}$$

Total costs C_t depend on the nonrecurring (investment costs) and annual costs (operating costs).[13] The total benefits B_t of a measure depend on the fuel reduction per year (in t) achieved by the measure and the bunker fuel price ($/t). The total CO_2 emission reduction potential $T*CO_2^{red}$depends on the effective duration of a measure *T* (or remaining lifetime of the ship if this is less than the effective duration of the measure) and the fuel reduction per year multiplied by the conversion factor 3.13. Investment costs are annuitized either over the effective duration of a measure or over the remaining lifetime of a ship in order to spread investment costs over years and to account for capital costs. The result can be interpreted as a measure's cost of abating a ton of CO_2 emissions (in net present value terms) when applied to a specific-ship segment/ship-age category.

We assume, following Faber et al. (2011a)/Wang et al. (2010), an interest and discount rate of 10% and bunker fuel prices amounting to $700 for the year 2020, $800 for the period 2021-2025, and $900 for the period 2026-2030.[14] In addition we also assume bunker fuel prices amounting to $900 for the period 2031 to 2050, albeit for measures with an effective lifetime of 30 years or more.

We analyze two scenarios to cover the extremes: one that assumes high reduction potentials and low costs (*hrlc*) and one that assumes low reduction potentials and high costs (*lrhc*) of

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[13] Faber et al. (2011a)/Wang et al. (2010) additionally take opportunity costs into account, i.e., the costs for extra time to implement measures on a ship.

[14] Sensitivity analysis shows that, in particular, fuel prices significantly affect the abatement costs of measures and, thus, the share of cost-effective reduction potential in the MACC , i.e., the share of measures that have negative abatement costs (Eide e al., 2009, Faber et al., 2011).

abatement measures. As Figure 2 shows, the difference between these two scenarios is mainly the amount of abatement potential at negative abatement costs and the level of these negative costs. The positive part of both curves is rather similar. How to treat the negative abatement costs it is thus very important. In this respect, we apply the three different approaches discussed in section 2.2:

The first MACC (case 1: *full reduction potential (full_rp)*) is a shifted-up version of the original MACC, where all parts of the MACC are above the horizontal axis.

The second MACC (case 2: *reduced reduction potential (reduced_rp*)) is a truncated version of the original MACC, where only the positive part of the MACC is taken into account and the emission reductions associated with negative abatement costs are subtracted from BAU emissions (original baseline).

The third MACC (case 3: *barrier reduction potential (barrier_rp*)) is a shifted-up version of a modified original MACC, where only measures which are subject to the issue of split incentives are taken into account.[15]

The resulting six MACCs (two different assumptions on abatement potential/abatement costs and three possibilities to deal with negative abatement costs) and the respective original and modified original MACCs (MACCs including negative marginal abatement costs) are presented in Figures 2a and 2b. Their corresponding maximum reduction potentials are presented in Table 3.

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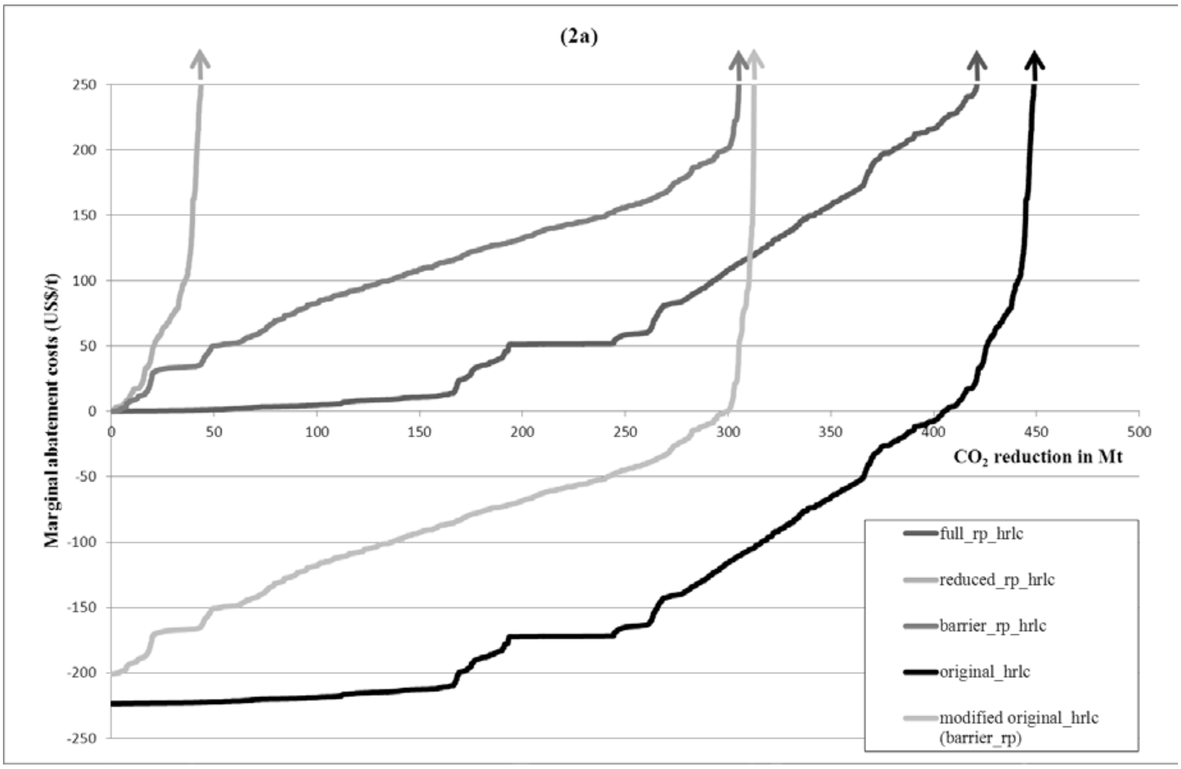
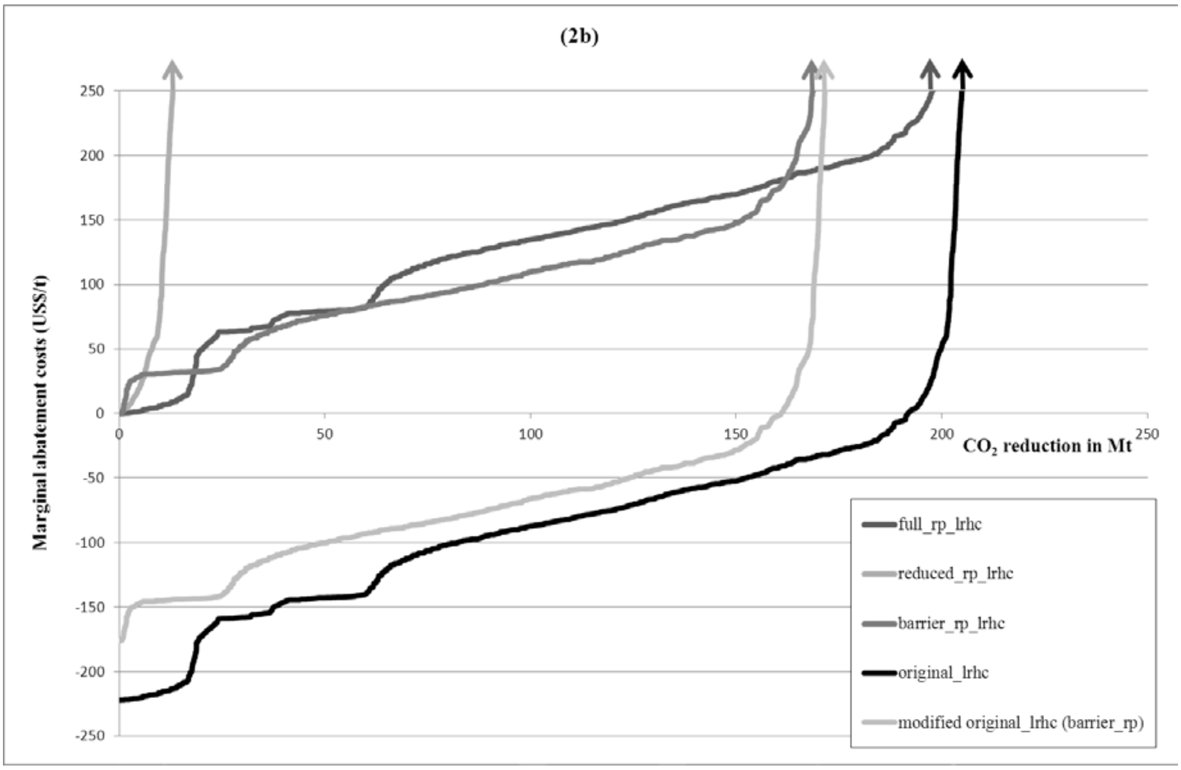
[15] The model results in cases *full_rp* and *reduced_rp* show a more moderate increase in marginal abatement costs per reduction potential in the beginning than in case *barrier_rp*. The latter case shows that a negligible share of the maximum reduction potential is available at very low marginal abatement costs (roughly -220 US$/t), which causes a jump in the beginning of the MACC. We eliminated that negligible share of the maximum reduction potential from the MACC (0.2% of reduction potential) because it would cause the shift-up of the MACC to be distorted. Instead, we shifted-up the MACC by using the constant 200.

Figures 2a and 2b: MACCs including negative abatement costs and MACCs relating to the three cases under the two reduction potentials and costs scenarios (2a: *hrlc and 2b: lrhc*)





Source: Own calculations.

Table 3: Maximum reduction potentials for the six cases in 2020

	hrlc			*lrhc*		
	full_rp	*reduced_rp*	*barrier_rp*	*full_rp*	*reduced_rp*	*barrier_rp*
CO_2 reduction potential in Mt	458	53	323	212	20	177

Source:Own calculations.

The three cases (*full_rp, reduced_rp, and barrier_rp*) differ in terms of maximum reduction potential and marginal abatement costs. The case *full_rp* always has the highest maximum reduction potential, followed by case *barrier_rp* and case *reduced _rp*. The maximum reduction potential in the *lrhc* scenario is less than 50% of that in the *hrlc* scenario. The share of maximum reduction potential that has negative (marginal abatement) costs is significant and amounts to about 90% in both scenarios. This is also apparent from the MACCs presented in Eide et al. (2011) and Faber et al. (2011a)/Wang et al. (2010), although it has to be remarked that their share of maximum reduction potential that has negative (marginal abatement) costs amounts to less than 90%. In Eide et al. (2011) it is 60% and in Faber et al. (2011a) it is 78%, but in Wang et al. (2010) it is roughly 90%. One explanation for this is that we base our calculations on the assumption that ships start to implement abatement measures in 2020 instead of 2007 as in Faber et al. (2011a) or 2008 as in Eide et al. (2011). As in previous studies, the fuel price is assumed to be higher as of 2020 and onwards, causing lower (marginal) abatement costs.[16] The maximum reduction potential of the case *barrier_rp* is less than that of the original MACC (70% in the *hrlc* scenario and 85% in the *lrhc* scenario) because specific measures are excluded a priori, so that their reduction potential is no longer available (we assume, rather, that it is already included in the BAU emissions). Moreover, it is apparent from the figures that the negative part of the MACC is more affected than the positive part of the MACC by the different reduction potentials/costs estimates.

We fit continuous functions by testing linear, quadratic, and exponential functional forms to each of the six MACCs for the fleet in order to obtain marginal abatement cost functions (*MAC(R)*), see Equation 2. We decided to use the linear and quadratic forms that show the best fit for the ranges of optimal abatement in the shipping sector as derived in our analysis

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[16] The (original) MACCs presented here differ also in terms of maximum reduction potentials and (marginal abatement) costs from the MACCs presented in Eide et al. (2011) and Faber et al. (2011a)/Wang et al. (2010). The reasons for this, in addition to the above mentioned one, are the following: we base our fleet development analysis on data from 2012 instead of 2008 or 2010, and we present MACCs based on 30 age categories instead of age-category averages.

(see Section 4.2), where we find that optimal abatement in the shipping sector is about 230 $MtCO_2$ maximum under the *hrlc* scenario and about 40 $MtCO_2$ under the *lrhc* scenario (see Equations 3, 4, 5).

$$MAC_{ij}\left(R_{ij}\right)=a_{ij}+b_{ij}R_{ij}+c_{ij}R_{ij}^2 , \qquad (2)$$

$$for\ i{=}1: a_{ij}=0 \wedge b_{ij}=0;\ j{=}1{:}\ 0 \le R_{ij} \le 300,\ j{=}2{:}\ 0 \le R_{ij} \le 30\ , \qquad (3)$$

$$for\ i{=}2: a_{ij}=0;\ j{=}1{:}\ 0 \le R_{ij} \le 25,\ j{=}2{:}\ 0 \le R_{ij} \le 10\ , \qquad (4)$$

$$for\ i{=}3: c_{ij}=0;\ j{=}1{:}\ 0 \le R_{ij} \le 75,\ j{=}2{:}\ 0 \le R_{ij} \le 50 , \qquad (5)$$

where *R* refers to emission reductions, *i* refers to cases (1) *full_rp*, (2) *reduced_rp*, and (3) *barrier_rp*, and *j* refers to (1) the *hrlc* scenario and (2) the *lrhc* scenario.

The parameters (a_{ij},b_{ij}, and c_{ij}), the R^2 (adjusted R^2), and function plots are presented in Table A1 and in Figures A1-A6 in the Appendix.

3 Combining the shipping MACC with a global MACC

3.1 Construction of a CGE-model-based global MACC

We use the DART (Dynamic Applied Regional Trade) CGE model, which is currently calibrated to the GTAP-7 database (Narayanan and Walmsley, 2008), to generate a global MACC for abatement measures used outside the shipping sector in 2020. The DART model is a multi-region, multi-sector recursive dynamic CGE model of the world economy designed for the analysis of international climate policies. For a more detailed description of the model see Klepper et al. (2003). The MACC contains options to reduce fossil fuel use, and thus to reduce CO_2 emissions, in all production and consumptions sectors of the world economy.[17] The shipping sector is not included in the DART model.[18]

The MACC of the DART sectors, which we denote in the following as all other sectors (*AoS*), is generated by implementing a harmonized global carbon tax of different levels in all model regions and then plotting the tax level, the carbon price, against the abatement (compared to a BAU emissions scenario without any climate policy or carbon price). To set up our partial

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[17] The production sectors are represented by coal, refined oil, gas, chemical products, electricity, agriculture, crude oil, transport, energy intensive sectors, other light industries, other heavy industries, and services. The consumption sector is represented by a representative household per region.

[18] The DART-model results are in 2004 US$. To compare the results to the shipping-model results, which are given in 2007 US$, we use the ratio 2007 US GDP Implicit Price Deflator/2004 US GDP Implicit Price Deflator.

MACC-based model, we again tested several functional forms to fit a continuous function to the MACC (see Figure A7 and A8 in the Appendix). Since it turns out in our scenario analysis that optimal abatement outside the shipping sector is always between 7,000 Mt CO_2 and 10,500 Mt CO_2 (see Section 4.2), we decided to use the quadratic form.

$$AC_{AoS}\left(R_{AoS}\right) = 0.0027 \cdot R_{AoS} + 2.6012 \cdot 10^{-7} \cdot R_{AoS}^2 \text{ , } 0 \le R_{AoS} \le 12000 \qquad (6)$$

with $R^2 = 0.999008$.

3.2 Discussion of combining both curves

We aim to obtain an idea of what amount of emission reduction in the shipping sector would constitute an efficient contribution to achieving the global reduction target. To do this, we make use of the least cost theorem (see, e.g., Perman et al., 1999) and combine both MACCs. We suppose that both *AoS* and shipping (*S*), have to achieve a given joint emission target, *A*. When both of them reduce their BAU emissions, E_i, by the amount R_i, the sum of individual emissions reductions thus needs to fulfil the overall condition

$$\sum_i \left(E_i - R_i\right) = A \text{ ,} \qquad (7)$$

where $i \in \{AoS, S\}$. The costs of achieving the emission target are measured by the abatement cost functions, $AC_i(R_i)$, and amount to $\sum_i AC_i\left(R_i\right)$. In both sectors, the optimal amount of emission reduction, R_i*, needs to be determined so that the sum of abatement costs is minimized. The optimization problem becomes:

$$\begin{aligned} &\min_{R_i} \sum_i C_i = \sum_i AC_i\left(R_i\right) \\ &s.t. \sum_i \left(E_i - R_i\right) \le A \wedge 0 \le R_i \le E_i \text{ .} \end{aligned} \qquad (8)$$

The optimization problem is, in general, solved by first setting up the first-order conditions[19] and second by solving the resulting equations simultaneously, which results in the marginal abatement costs being equal to the shadow price, $p*$, (tax or permit price) of the emission constraint (=target) over both sectors:

$$AC_i^{'}\left(R_i^*\right) = p^* \text{ .} \qquad (10)$$

We are aware that the combination of both MACCs is in fact not entirely consistent because they are different by construction. The calculation of mitigation costs is based on a project-

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[19] We obtain the marginal abatement costs functions directly from the MACC analysis.

level analysis in the shipping framework, whereas the calculation is based on a macro-economic analysis in the DART model. The former analysis assumes that the implementation of individual (abatement) measures do not affect prices and markets indirectly, whereas the latter analysis takes into account general equilibrium effects of climate policies that affect prices and markets. However, the impact of abatement measures in the shipping sector on prices and markets can be assumed to be small and thus the inaccuracy of combining both MACCs should be rather small as well.

4 Analysis of different emission reduction and climate policy scenarios

4.1 Description of scenarios

Before we describe the emission reduction and policy scenarios for our analysis, we need to describe the BAU emission scenarios of the two sectors under consideration: AoS and shipping. Knowledge of their BAU emissions is necessary in order to determine the emission reductions both sectors have to achieve under the reduction scenarios. The BAU emissions of AoS amount to 34.5 $GtCO_2$ in 2020 according to the DART model. This number includes the CO_2 emissions of all the production and consumption sectors of the world economy, except the ones caused by shipping and aviation. The BAU emissions of shipping depend on the case analyzed. In cases *full_rp* and *barrier_rp*, the BAU emissions amount to 0.947 $GtCO_2$ in 2020 according to our calculations. In case *reduced_rp*, the BAU emissions need to be corrected by the emission reduction potential that can be achieved at negative abatement costs (0.405 $GtCO_2$ in *hrlc* and 0.192 $GtCO_2$ in *lrhc*) because we assume that this potential is achieved even in the absence of any climate policy. As a result, the BAU emissions of shipping amount to 0.542 $GtCO_2$ under the *hrlc* scenario and 0.755 $GtCO_2$ under the *lrhc* scenario. The BAU emissions of aviation amount to 0.494 $GtCO_2$ in 2020 according to the IEA (2009a).

Now we can proceed to describe the emission reduction scenarios, of which there are three, each of which differ in terms of the assumed global reduction requirements. In the first scenario, the global reduction requirement is determined by the 2°C target, which was acknowledged by the Copenhagen Accord and the G8 summit. In the other two scenarios, the global reduction requirement is determined by the Copenhagen Pledges, which consist of an unconditional (CP low) and conditional (CP high) pledge scenario. These pledges are national reduction pledges for 2020, which have been submitted by many Annex 1 and non-Annex 1 countries to the UNFCCC in the context of the Copenhagen meeting (UNFCCC, 2010a,b,c) and which are the only targets – though nonbinding - that exist.

Concerning the 2°C target, the UNEP report (UNEP, 2010) assumes that an overall greenhouse gas emission level of 45 $GtCO_2$-eq needs to be reached in 2020 to have a 50-66% chance of meeting the 2°C target. For our analysis, we need to derive a target for CO_2 emissions of the sectors covered in the DART model plus the shipping sector. To do so, we assume that the GHG share of CO_2 emissions resulting from fossil fuel use, which was according to IPCC (2007) 56.6% in 2004, stay constant over time. Consequently, around 25.47 $GtCO_2$ emissions from fossil fuel use can be emitted in 2020. This still includes 0.494 $GtCO_2$ emitted by aviation in 2020 (IEA, 2009a). Since we assume that aviation has no obligation to abate emissions, we also assume that these emissions stay constant and subtract them from 25.47 $GtCO_2$ to arrive at our final 2°C target of 24.796 $GtCO_2$ for the sectors covered in our analysis.

Concerning the Copenhagen Pledges, the low pledges from all countries would – according to den Elzen et al. (2011) – lead to a global emission level of 49.7 $GtCO_2$-eq and the high pledges to a level of 48.6 $GtCO_2$-eq in 2020. These numbers include the CO_2 emissions of international bunkers (and thus of shipping and aviation combined), which amount to 1.1 $GtCO_2$ and are thus not consistent with our own BAU shipping emissions and the aviation emissions published by the IEA (2009a). To be consistent in our scenarios, we thus subtract these 1.1 $GtCO_2$ and add our BAU shipping emissions (0.947 $GtCO_2$ (*hrlc* and *lrhc*) in cases *full_rp* and *barrier_rp* and 0.542 $GtCO_2$ (*hrlc*) and 0.755 $GtCO_2$ (*lrhc*) in case *reduced_rp*) and the aviation emissions of 0.494 $GtCO_2$ published by the IEA (2009a) instead. The "revised Copenhagen Pledges" then amount to 50.041 $GtCO_2$, respectively, 49.636 $GtCO_2$ (*hrlc*) and 49.849 $GtCO_2$ (*lrhc*) in case *reduced_rp*, in the low pledges and 48.941 $GtCO_2$, respectively, 48.536 $GtCO_2$ (*hrlc*) and 48.749 $GtCO_2$ (*lrhc*) in case *reduced_rp*, in the high pledges scenario. Again, we then multiply these targets by 0.556 to obtain a target for CO_2 emissions only and finally subtract aviation emissions. Table 4 shows the BAU emissions, emission targets, and implied reduction targets for our different scenarios.

Table 4: Emission targets, BAU emissions, and implied reduction targets

	Targets ($CO_{2eq.}$)	Revised Copenhagen Pledges ($CO_{2eq.}$)		Targets for AoS and S		∑ BAU emissions AoS and S		Reduction targets AoS+shipping	
Cases		*full_rp & barrier_rp*	*reduced_rp*	*full_rp & barrier_rp*	*reduced_rp*	*full_rp & barrier_rp*	*reduced_rp*	*full_rp & barrier_rp*	*reduced_rp*
2°C	45.000			24.976		35.447	35.042/35.255	*29.5%*	*28,4%/29.0%*
CP low	49.700	50.041	[a]49.635 / 49.849	27.829	[a]27.600/27.721	35.447	35.042/35.255	*21.0%*	*21,2%/21.4%*
CP high	48.600	48.941	[a]48.953/48.749	27.207	[a]26.977/27.098	35.447	35.042/35.255	*23.0%*	*23,2%/23.1%*

[a] Revised numbers for case *reduced_rp* under the *hrlc* and *lrhc* scenarios.

Source: den Elzen et al. (2011), UNEP (2010), IEA (2009a), and own calculations.

The aim of our analysis is to assess for three different global reduction targets (a) the maximum global cost savings that could be achieved by emission abatement in the shipping sector, (b) the cost efficient abatement contributions of the shipping sector to the global reduction targets, and (c) the potential additional costs that would be incurred by implementing a separate solution for the shipping sector. We base our analysis on two alternative policy scenarios. One policy scenario assumes that AoS and shipping have a joint target, i.e., both sectors contribute (efficiently) to the joint overall reduction target (*joint target* scenario). The other policy scenario assumes that AoS has to bear the full reduction burden, while the shipping sector remains unregulated (*AoS without shipping* scenario). Comparing both scenarios indicates the potential gains that could be achieved by including the shipping sector in climate policy on CO_2 emission reductions.

4.2 Results

We start by discussing the results of the policy scenario *joint target* (these results are also summarized in Table 5) and thereafter discuss the results of the comparison between the policy scenario *joint target* and policy scenario *AoS without shipping*.

The CO_2 prices range, depending on the case analyzed and assumed reduction potentials/ costs scenario (*hrlc* and *lrhc*), between \$53.5 and \$56.8 under the 2°C target, between \$34.5 and \$35.7 under the low Copenhagen Pledges, and between \$38.7 and \$39.9 under the high Copenhagen Pledges. CO_2 prices are always higher in the *lrhc* scenario than in the *hrlc* scenario because it has a smaller reduction potential and higher cost per abated ton of CO_2. CO_2 prices are always the lowest in case *reduced_rp*, independent of the assumed reduction potentials/costs scenario (*hrlc* or *lrhc*), because the BAU emissions in cases *full_rp* and *barrier_rp* are higher than in case *reduced_rp*, causing higher reduction needs.

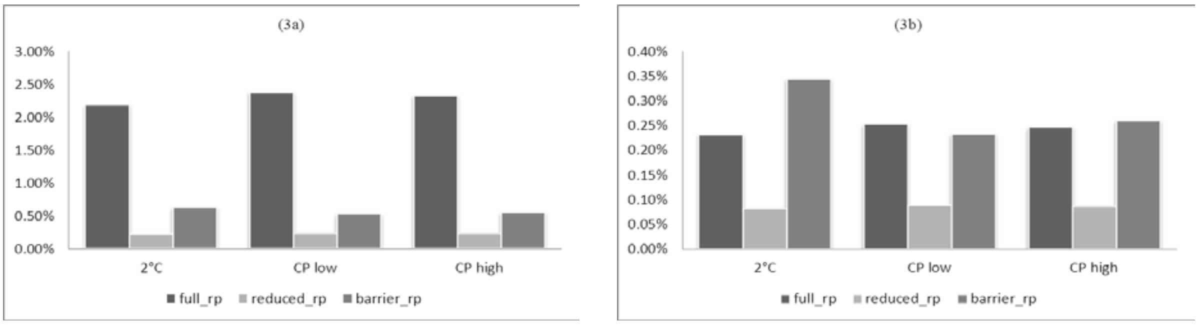
Table 5: CO_2 prices, efficient reduction relative to BAU emissions and to overall target

		2°C			CP low			CP high		
Reduction/ costs scenario	Cases	CO_2 price	R_S rel.to BAU emissions	R_S rel.to overall target	CO_2 price	R_S rel.to BAU emissions	R_S rel.to overall target	CO_2 price	R_S rel.to BAU emissions	R_S rel.to overall target
hrlc	*full_rp*	55.11	24.2%	2.19%	34.59	19.2%	2.38%	38.71	20.28%	2.33%
	reduced_rp	53.52	4.1%	0.22%	34.51	3.3%	0.24%	38.70	3.47%	0.23%
	barrier_rp	56.43	6.9%	0.63%	35.52	4.3%	0.53%	39.73	4.80%	0.55%
lrhc	*full_rp*	56.77	2.6%	0.23%	35.66	2.0%	0.25%	39.91	2.15%	0.25%
	reduced_rp	55.34	1.1%	0.08%	35.20	0.9%	0.09%	39.42	0.93%	0.09%
	barrier_rp	56.67	3.8%	0.34%	35.67	1.9%	0.23%	39.90	2.26%	0.26%

Source: Own calculations.

The efficient contribution of shipping to overall reductions varies between 0.1% and 2.2% under the 2°C target, between 0.1% and 2.4% under the low Copenhagen Pledges, and between 0.1% and 2.3% under the high Copenhagen Pledges. It is the highest in case *full_rp*, followed by case *barrier_rp* and case *reduced_rp* in the *hrlc* scenario (see Figure 3a). The reason for this is that the MACCs of cases *full_rp* and barrier*_rp* have higher maximum reduction potentials and are less steep in the beginning than in case *reduced_rp* (see Figure A9 in the Appendix). The picture is different in the *lrhc* scenario. The efficient contribution of shipping to overall reductions is the highest in case *barrier_rp* (except under the *low* Copenhagen Pledges scenario), followed by case *full_rp* and case *reduced_rp* in the *lrhc* scenario (see Figure 3b). Here, the MACCs of cases *full_rp* and *reduced_rp* are steeper in the beginning, but start at a lower cost level than case *barrier_rp* (see Figure A9 in the Appendix). Moreover, the lower the overall reduction target (CP *low* < CP *high* < 2°C), the higher the efficient contribution of shipping to the overall target in cases *full_rp* and *reduced_rp* in both of the reduction potentials and costs scenarios (*hrlc* and *lrhc*) assumed. This is caused by the quadratic functional form of the approximated MAC functions. The opposite, i.e., the lower the overall reduction target (CP *low* < CP *high* < 2°C), the lower the efficient contribution of shipping to the overall target, is true for case *barrier_rp*. This is caused by the linear functional form of the approximated MAC functions.

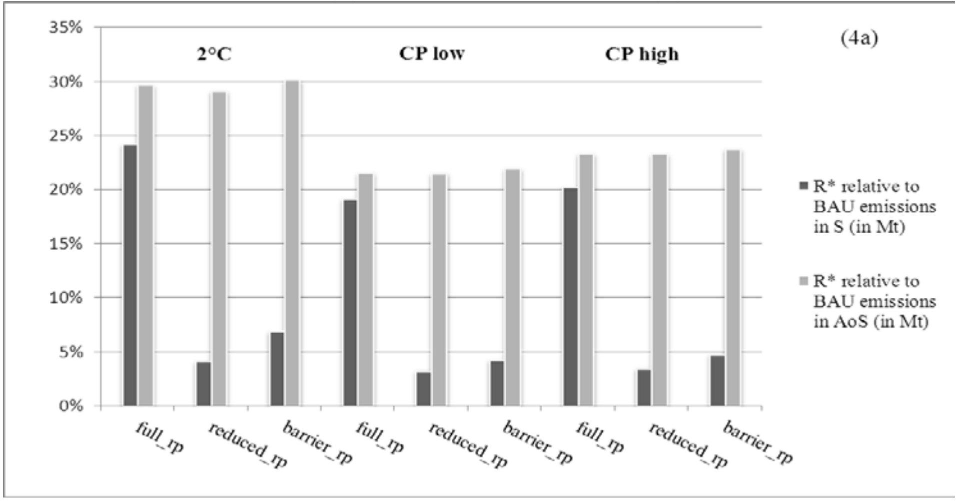
Figures 3a and 3b: Efficient contribution of shipping to the three overall reduction targets in the *hrlc* scenario (a) and the *lrhc* scenario (b)

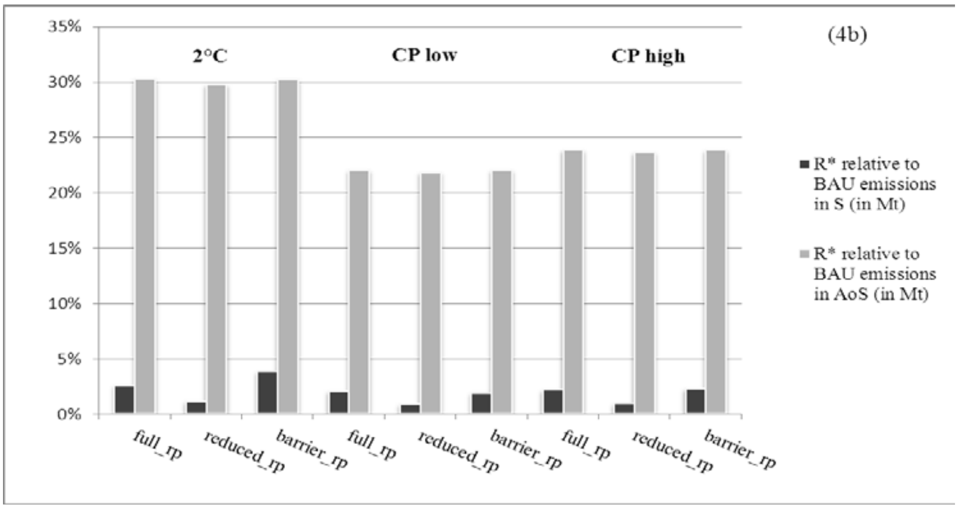


Source: Own calculations.

The emission reductions of the shipping sector relative to its BAU emissions range, depending on the analyzed case and assumed reduction potentials/costs scenario, between 1% and 24% under the 2°C target, between 1% and 19% under the low Copenhagen Pledges, and between 1% and 20% under the high Copenhagen Pledges. Emission reductions relative to BAU emissions are always the highest in case *full_rp*, followed by case *barrier_rp* and case *reduced_rp* in the *hrlc* scenario. The order changes in the *lrhc* scenario. Here, emission reductions relative to BAU emissions are always the highest in case *barrier_rp*, followed by case *full_rp* and case *reduced_rp*, except under the low Copenhagen Pledges. The reason for this is that the increase in marginal abatement costs is less steep in case *barrier_rp* (see Figure A15). Emission reductions relative to BAU emissions in AoS range between 29% and 30% under the 2°C target, between 21% and 22% under the low Copenhagen Pledges, and between 23% and 24% under the high Copenhagen Pledges. Figures 4a and 4b compare the efficient emission reductions relative to BAU emissions in shipping and AoS.

Figures 4a and 4b: Comparison of efficient emission reductions relative to BAU emissions of AoS and S (a) in *hrlc* scenario and (b) in *lrhc* scenario



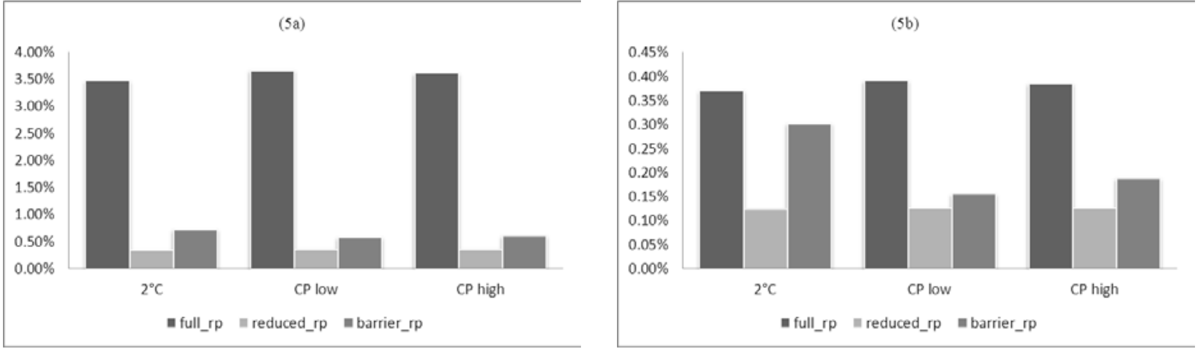


Source: Own calculations.

They show, first, that the variation between the different shipping cases is higher in the *hrlc* scenario (Figure 4a) than in the *lrhc* scenario (Figure 4b), second, that efficient emission reductions relative to BAU emissions in shipping and AoS are only similar in the case *full_rp* in the *hrlc* scneario. In all other cases, the relative reductions of shipping are significantly lower than the ones of AoS. This has policy implications, which we discuss in Section 5.

Now, we discuss the results of the comparison between the policy scenario *joint target* and the policy scenario *AoS without shipping*, i.e., the scenario where only AoS has to bear the entire reduction burden. The results are shown in the following Figures 5a and 5b.

Figures 5a and 5b: Relative global cost savings of the two policy scenarios: (a) AoS and S have a joint target versus AoS without S in the *hrlc* scenario and (b) AoS and S have a joint target versus AoS without S in the *lrhc* scenario



Source: Own calculations.

The relative cost savings range, depending on the case analyzed and reduction potentials and costs scenario assumed, between 0.1% and 3.5% under the 2°C target, between 0.1% and 3.7% under the low Copenhagen Pledges, and between 0.1% and 3.6% under the high Copenhagen Pledges. The relative cost savings are always positive if AoS and shipping have a joint target because shipping contributes an additional reduction potential at low (marginal) abatement costs. Naturally, the cost savings are larger under the optimistic *hrlc* scenario than in the pessimistic *lrhc* scenario. The relative cost savings are always the highest in case *full_rp*, followed by case *barrier_rp* and *reduced_rp*.

The change in CO_2 prices compared to the joint reduction scenario is small (< 1%) in all the cases and under all the reduction scenarios. Only in case *full_rp* under the *hrlc* scenario, where shipping contributes significantly more to overall reduction than in all other cases under both reduction potentials and costs scenarios assumed, does the CO_2 price increase by more than 3% under all reduction scenarios. When looking at the share of shipping's abatement costs (AC_S) in overall abatement costs ($AC_{AoS}+ AC_S$), this is smaller than the share of its reductions (R_S) in overall reductions ($R_{AoS}+ R_S$) in most cases under the *hrlc* and *lrhc* scenarios. Thus, overall cost savings are higher than the mere share of reductions in the shipping sector suggests. While the shipping sector overall does not contribute a large share of reductions, the potential reduction measures are relatively cheap. Case *barrier_rp* is the only exception under all three global reduction target scenarios.

Tables A2-A4 in the Appendix provide more results (in absolute terms) of the three global reduction requirement scenarios.

5 Discussion

Our results show that the shipping sector could always contribute to efficient global emission reductions and that this contribution could always achieve global cost savings. However, the contribution of the shipping sector to efficient global emission reductions and the potential cost savings depend to a large degree on the MACC case assumed, i.e., depend on how the existence of negative abatement costs is treated in a MACC, and on the reduction potentials and costs of measures assumed.

If we are generally optimistic about reduction potentials and costs (*hrlc* scenario), the contribution and potential cost savings are significant in the case with the highest maximum reduction potential (*full_rp*), almost negligible in the case with the smallest maximum reduction potential (*reduced_rp*), and small in the case with the moderate maximum reduction potential (*barrier_rp*). The reasons for this are obviously that in case *barrier_rp*, fewer measures are taken into account and in case *reduced_rp*, a huge share of the maximum reduction potential (the reduction potential at negative costs) is assumed to be achieved even in the absence of climate policy, so that this reduction potential no longer contributes to cost savings when regulating the shipping sector. Thus, only a small share of the maximum reduction potential remains. However, it is difficult to say which of the cases resulting from the approaches presented in Section 2.2 is most realistic. We clearly believe that there are barriers to implementation that have some kind of shadow price so that we see the second approach as rather academic. Therefore, its corresponding case (*reduced_rp*), the one with the smallest maximum reduction potential, seems to be less realistic than the other two cases because it assumes that all reduction potentials at negative costs will be implemented, i.e., that there are no barriers to implementation or extra costs, whereas both cases, *full_rp* and *barrier_rp*, assume that barriers to implementation or extra costs exist. However, the case *barrier_rp* might underestimate the reduction potential by excluding measures from the MACC analysis that are assumed to be already used by a significant share of the world fleet.

The opposite might be true for case *full_rp* by assuming that all the analyzed measures are not being used yet. Moreover, shifting up the MACC by exactly the level of the measure with the highest negative costs involves making an arbitrary choice. Extra costs could be even higher (or lower), affecting the contribution of shipping to efficient abatement. Nevertheless, we suggest that the case with the highest maximum reduction potential (*full_rp*) should be considered the most realistic one.

If we are generally pessimistic about reduction potentials and costs (*lrhc* scenario) the general picture is different. Now global cost savings are almost negligible (in the order of less than 0.5%) and there is no significant difference between cases *full_rp* and *barrier_rp*.

Comparing the two reduction potential and costs scenarios (*hrlc/lrhc*) shows that the difference between the maximum reduction potentials is large, the difference between the marginal abatement costs is not so obvious (see Figure 2a and 2b). Thus, results are more affected by the assumption about the potential reduction effects of measures than by the assumption about the range of potential costs (see in addition the discussion in Eide et al., 2011). Consequently, more research should be conducted in order to reduce the uncertainty about the potential performance of measures, i.e., to minimize the range of a measure's potential reduction effect.

Comparing the three emission reduction scenarios, the status of today's climate negotiations suggests that the scenario low Copenhagen Pledges will be the most realistic one. This scenario is in favor of the inclusion of the shipping sector. The smaller the joint reduction target is, the larger the shipping sector's relative contribution is to efficient global emission reductions in cases *full_rp* and *redcued_rp*. This implies that the shipping sector accommodates a small, but at the same time, a cost-effective reduction potential that should be exploited for global emission reductions.

The results for all the scenarios also provide us with an idea of what the efficient reduction targets should be when a separate solution for the shipping sector is the regulatory choice. The separate solution is being discussed in the IMO, as mentioned in the Introduction, but also in the EU. The Council of the European Union (2009) proposed a 20% reduction target for the shipping sector below 2005 by 2020.[20] Our calculations show that this target is close to the cost minimizing reduction level when assuming high reduction potentials and low costs (*hrlc*

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[20] The reduction in absolute terms would be ~311 $MtCO_2$. We based the calculation on the emission estimate for 2005 in Buhaug et al. (2009) and the BAU emissions used in this paper.

scenario) and the full reduction potential (*full_rp*). When we compare to this target our targets implied by the Copenhagen pledges, we find that there is in this case a perfect match, while we find in the case of the 2°C target that the optimal reduction target in the shipping sector would be about 25%. Under these assumptions, requiring the same relative reductions in the shipping sector and AoS is thus almost cost efficient. Under all other assumptions (low abatement potentials and higher costs – i.e., all *lrhc* scenarios and all *reduced_rp* and *barrier_rp* scenarios), the relative reduction target for the shipping sector that is cost minimizing is much lower than 20% and mostly in the order of a 1 – 5% reduction only.

A comparison to the other studies (see Table 1) shows that the shipping sector's cost-effective reduction potential becomes considerably smaller when treating the existence of negative marginal abatement costs as a calculation artifact caused by the narrow cost definition of project-level analysis (our scenarios *full_rp* and *barrier_rp*). According to Eide et al. (2011), emission reductions in the order of between 27% and 31% relative to BAU emissions could be achieved in 2020 if a decision criterion (marginal cost threshold) of <20US$/t, <50US$/t, respectively, were to be applied. These emission reductions include not only reductions that have positive costs, but also the ones that have negative costs. We, on the other hand, found that (efficient) emission reductions amounts to 19% relative to BAU emissions in the most optimistic scenario (*full_rp/hrlc*) and to only 1% in the most pessimistic case (*reduced_rp/lrhc*) under the low Copenhagen Pledges (~35US$/t).

6 Conclusion

While it is clear that emissions generated by the shipping sector are substantial and can be reduced, at least partially, at low costs it has not been analyzed so far how much emissions should actually be reduced when the objective is to reach a given global emission target at minimal costs. In this paper, we have thus determined whether the shipping sector could contribute to reducing global emissions efficiently to reach certain global emission targets under different policy scenarios by making use of marginal abatement cost curves (MACC). We have presented an approach to deal with the existence of negative abatement costs in the expert-based MACC generated for the shipping sector in order to combine it with a CGE model-based MACC generated for abatement measures used outside the shipping sector. We focus on the year 2020.

The main findings are that the shipping sector could always contribute to efficient global emission reductions and thus could always achieve global cost savings. Yet, the optimal contribution and the possible cost savings depend much on the MACC case assumed, i.e., depend on how the existence of negative abatement costs in a MACC is treated, and the assumed reduction potentials and costs of measures. Under optimistic assumptions about the use of abatement measures, the shipping sector can reduce costs by 3.5%, while under less optimistic assumptions it can only reduce costs by less 1%.

Yet, it is important to point out that we did not have data for the reduction potentials and costs of all possible abatement measures in the shipping sector and also since we only included 14 ship types, representing only a part of the world fleet, although this part is significant in terms of transported tonnage. This implies that the reduction potential might increase when more measures and more ship types are included in the analysis.

Overall, we thus conclude that emissions generated in the shipping sector should be regulated in order to prevent emissions generated by the shipping sector from consuming a considerable share of allowed emissions in the coming decades and to prevent other sectors from having to compensate by exploiting more expensive abatement options. Since there is uncertainty about what the optimal reduction level in the shipping sector would be, an approach that allows equalization of marginal abatement costs in the shipping sector and other sectors (such as including the shipping sector in an emission trading scheme or applying a carbon tax at a level of prices in existing emission trading schemes) is preferable to isolated regulation of the shipping sector.

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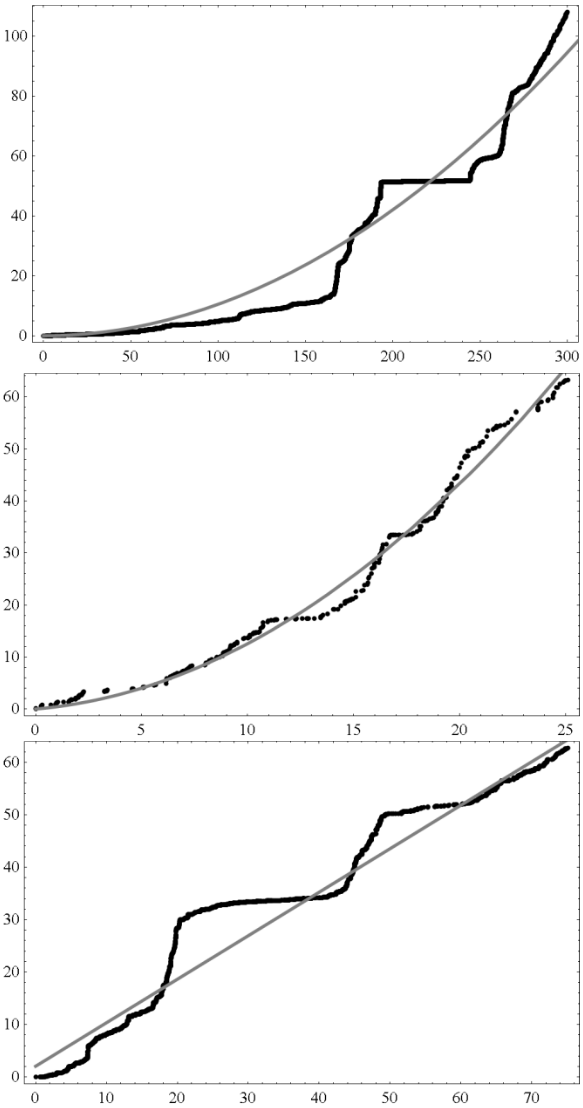
Appendix

Table A1: Parameter values and (adjusted) R^2 of approximated marginal abatement cost functions.

Case	Reduction and costs scenario	Parameter values			R^2	adj.R^2
		a	b	c		
full_rp	*hrlc*			0.00105054	0.980893	0.980891
	lrhc			0.09675131	0.968225	0.968214
reduced_rp	*hrlc*		0.34804264	0.09087283	0.995681	0.995653
	lrhc		1.36010899	0.60900788	0.997943	0.997940
barrier_rp	*hrlc*	2.054096808	0.82941192		0.968542	
	lrhc	15.28405984	1.15011927		0.851306	

Figures A1-A3 show the approximated functions for the high reduction and low costs scenario (*hrlc*) and Figures A4-A6 show the approximated functions for the high reduction and low costs scenario (*lrhc*).

A1-A3



A4-A6

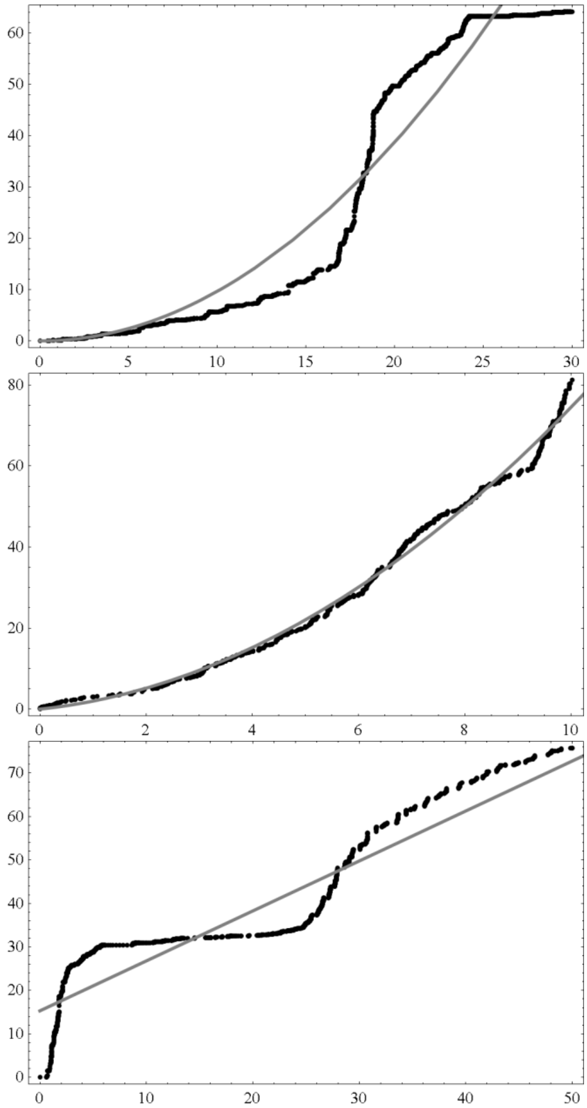
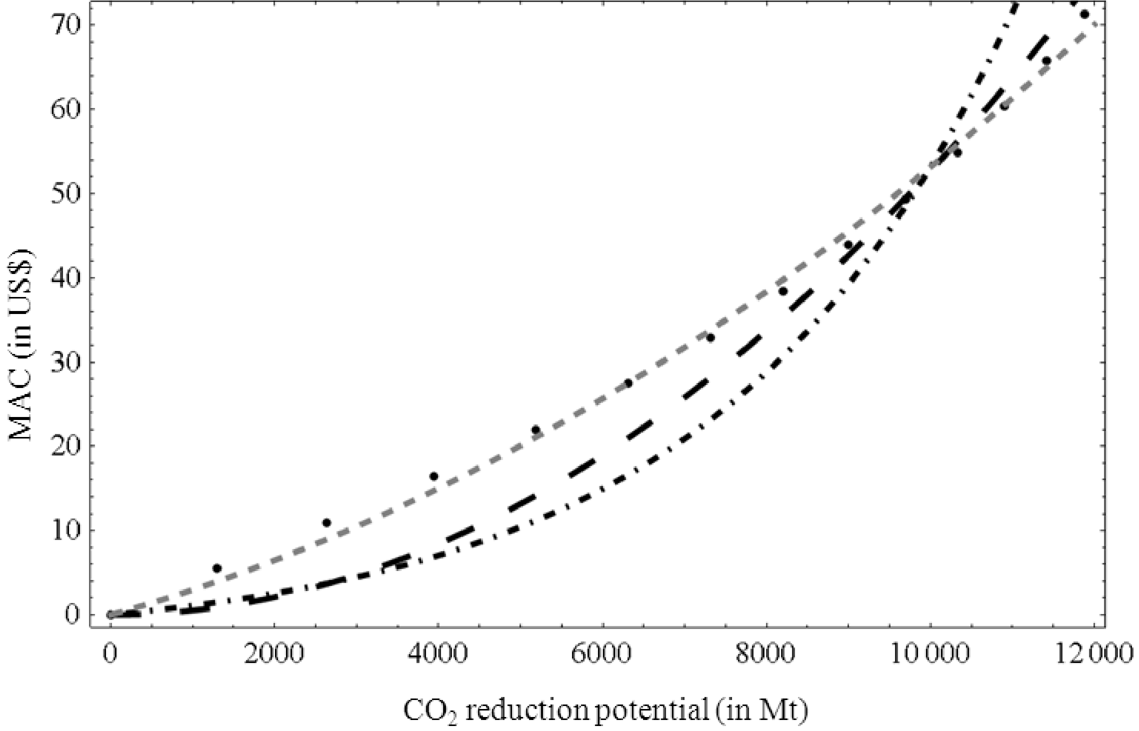


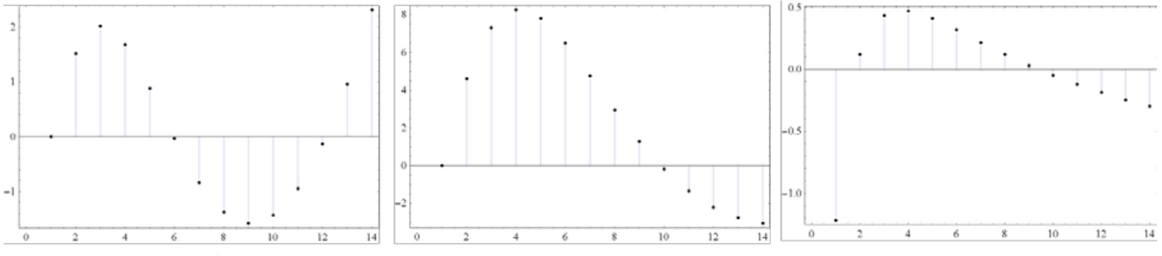
Figure 7 shows three approximated functions for AoS. As the figure shows, the quadratic form (gray dashed line: $bx+cx^2$) has a better fit than the other quadratic (black dashed line: cx^2) and the exponential form (black dotted-dashed line: Exp(a+bx)) for abatement levels between 7,000 and 10,500 $MtCO_2$.

Figure A7: Comparison of functional fits with global (AoS) MACC



Source: Own presentation. MACC generated with the DART model.

Figure A8: Residuals plots



$bx+cx^2$ cx^2 Exp(a+bx)

Figure A9: Global (AoS) MACC and shipping MACCs

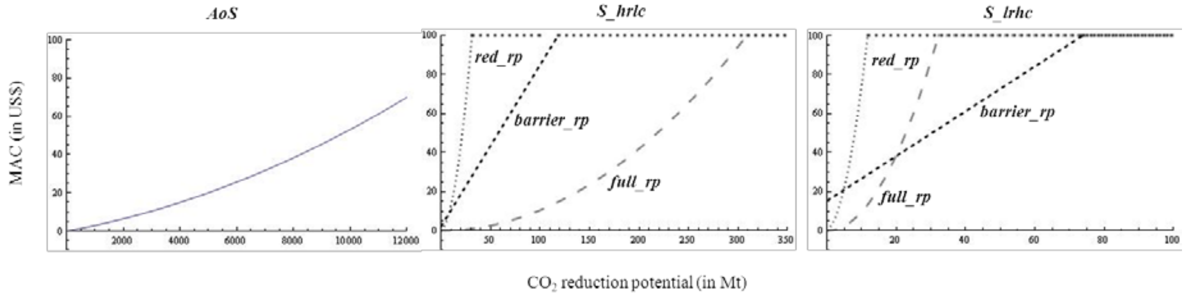


Table A2: Emissions, abatement costs, and prices under the 2°C target

Policy scenario	Reduction and costs scenario	Cases	Business-as-usual emissions shipping and AoS (in Mt)	Emissions after efficient reduction (in Mt) in shipping sector	Emissions after efficient reduction (in Mt) in AoS	Abatement costs shipping (AC_S in billion 2007US$)	Abatement costs AoS (AC_{AoS} in billion 2007US$)	Abatement costs ($AC_{AoS} + AC_S$ in billion 2007US$)	CO_2 price/ton (in 2007US$)= MAC_{AoS}	CO_2 price/ton (in 2007US$) $=MAC_{AoS}=MAC_S$
Joint target for AoS and shipping	*hrlc*	*full_rp*	947 34500	718	24258	4.21	235.65	239.86		55.11
		reduced_rp	542 34500	519	24456	0.43	224.87	225.30		53.52
		barrier_rp	947 34500	881	24095	1.92	244.76	246.68		56.43
	lrhc	*full_rp*	947 34500	922	24053	0.46	247.10	247.56		56.77
		reduced_rp	755 34500	746	24230	0.17	237.22	237.39		55.34
		barrier_rp	947 34500	911	24065	1.29	246.43	247.72		56.67
AoS without shipping	*AoS (DART)*	*full_rp*	34500		24029		248.48		56.97	
		reduced_rp	34500		24434		226.07		53.70	
		barrier_rp	34500		24029		248.48		56.97	
	AoS (DART)	*full_rp*	34500		24029		248.48		56.97	
		reduced_rp	34500		24221		237.69		55.41	
		barrier_rp	34500		24029		248.48		56.97	

Table A3: Emissions, abatement costs, and prices under the low Copenhagen Pledges target

Policy scenario	Reduction and costs scenario	Cases	Business-as-usual emissions shipping and AoS (in Mt)	Emissions after efficient reduction (in Mt) in shipping sector	Emissions after efficient reduction (in Mt) in AoS	Abatement costs shipping (AC_S in billion 2007US$)	Abatement costs AoS (AC_{AoS} in billion 2007US$)	Abatement costs ($AC_{AoS} + AC_S$ in billion 2007US$)	CO_2 price/ton (in 2007US$)= MAC_{AoS}	CO_2 price/ton (in 2007US$) $=MAC_{AoS}=MAC_S$
Joint target for AoS and shipping	*hrlc*	*full_rp*	947 34500	765	27063	2.09	110.78	112.87		34.59
		reduced_rp	542 34500	524	27076	0.22	110.36	110.58		34.51
		barrier_rp	947 34500	906	26922	0.76	115.73	116.49		35.52
	lrhc	*full_rp*	947 34500	927	26901	0.23	116.48	116.71		35.66
		reduced_rp	755 34500	748	26972	0.09	113.99	114.07		35.20
		barrier_rp	947 34500	929	26900	0.45	116.53	116.98		35.67
AoS without shipping	*AoS (DART)*	*full_rp*	34500		26882		117.17		35.79	
		reduced_rp	34500		27058		110.97		34.62	
		barrier_rp	34500		26882		117.17		35.79	
	AoS (DART)	*full_rp*	34500		26882		117.17		35.79	
		reduced_rp	34500		26965		114.22		35.24	
		barrier_rp	34500		26882		117.17		35.79	

Table A4: Emissions, abatement costs, and prices under the high Copenhagen Pledges target

Policy scenario	Reduction and costs scenario	Cases	Business-as-usual emissions shipping and AoS (in Mt)	Emissions after efficient reduction (in Mt) in shipping sector	Emissions after efficient reduction (in Mt) in AoS	Abatement costs shipping (AC_S in billion 2007US$)	Abatement costs AoS (AC_{AoS} in billion 2007US$)	Abatement costs ($AC_{AoS} + AC_S$ in billion 2007US$)	CO_2 price/ton (in 2007US$)= MAC_{AoS}	CO_2 price/ton (in 2007US$) $=MAC_{AoS}=MAC_S$
Joint target for AoS and shipping	*hrlc*	*full_rp*	947 34500	755	26452	2.48	133.18	135.66		38.71
		reduced_rp	542 34500	523	26454	0.26	133.11	133.37		38.70
		barrier_rp	947 34500	901	26305	0.95	138.93	139.88		39.73
	lrhc	*full_rp*	947 34500	926	26280	0.27	139.93	140.20		39.91
		reduced_rp	755 34500	748	26350	0.10	137.16	137.26		39.42
		barrier_rp	947 34500	925	26281	0.59	139.89	140.48		39.90
RoW without shipping	*AoS (DART)*	*full_rp*	34500		26260		140.74		40.05	
		reduced_rp	34500		26435		133.84		38.83	
		barrier_rp	34500		26260		140.74		40.05	
	AoS (DART)	*full_rp*	34500		26260		140.74		40.05	
		reduced_rp	34500		26343		137.44		39.47	
		barrier_rp	34500		26260		140.74		40.05	