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Marginal abatement cost curves for CO_2 emission reduction from shipping to 2050

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A B S T R A C T

The International Maritime Organization (IMO) has stated an ambition to achieve net-zero GHG emissions by 2050 and new regulations are under development to achieve this. To inform decisions on GHG regulations, this study has modeled the CO_2 emission abatement potentials and costs towards 2050 for all ships above 400 gross tons. We explore CO_2 reduction pathways based on marginal abatement cost curves (MACC) for 2030, 2040 and 2050. MACC is an important tool to assess the potential impact of regulations and can inform current policy debates as well as ship owners that need to develop their decarbonization strategies. Compared to previous work, we provide global MACCs taking into account the latest technologies and cost development, including alternative fuels. The updated MACC is based on more than 50 state-of-the-art abatement measures, 10 fuel systems and 8 fuels. The results indicate that the revised IMO GHG strategy ambition of 20–30 % GHG emission reduction in 2030, relative to 2008, can be reached at a marginal cost of 50–100 USD/tCO_2; 70–80 % emission reduction in 2040 can be achieved at 230–240 USD/tCO_2 and net-zero emissions in 2050 at a marginal cost of 300 USD/tCO_2. The two inputs which have the highest impact on the results are the future cost of carbon-neutral fuels and growth in seaborne trade.

1. Introduction

The world shipping fleet emitted just above 1 billion tonnes CO_2e in 2018, of which 98 % were CO_2 emissions, contributing to about 2.9 % of the global anthropogenic greenhouse gas (GHG) emissions (Faber et al., 2020). In 2023 the International Maritime Organization (IMO) adopted its revised GHG reduction strategy (IMO, 2023) stating the ambition to reach net-zero emissions from international shipping 'by or around (i.e. close to) 2050′, as well as indicative checkpoints to reach 20 %, striving for 30 %, total GHG emission reduction in 2030, and 70 %, striving for 80 %, reduction in 2040. The reduction targets are relative to 2008 and should be considered in a well-to-wake perspective.

The strategy also sets out a timeline to finalize a 'basket' of regulatory GHG reduction measures by 2025 to achieve the ambitions, which should consist of a technical element regulating the GHG emission intensity of marine fuels, as well as an economic element on the basis of a GHG pricing mechanism. If adopted in 2025, these regulations would take affect from 2027. At the same time the EU will

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include shipping into its emission trading system (ETS) from 2024 and impose a well-to-wake GHG intensity requirement on energy used from 2025 (EU, 2023a, 2023b).

Achieving IMO's and EU's policy ambitions will require uptake of a range of abatement measures in the shipping fleet in the years to come (Hellström et al., 2024; Faber et al., 2020; Bouman et al., 2017). These range from hull and machinery improvements, operational measures and speed reductions, to alternative carbon-neutral[2] fuels like biodiesel, hydrogen and ammonia, as well as onboard carbon capture and subsequent storage. Some measures like speed reduction and energy efficiency improvements will result in fuel cost reductions, while carbon-neutral fuels will incur significant cost increases (Martin et al., 2023; Schwartz et al., 2020; Bouman et al., 2017).

With the ongoing implementation discussion on further regulatory measures in shipping, updated state-of-the-art marginal abatement cost curves (MACC or MAC curves) are essential. A MACC shows the increase in abatement cost of a marginal increase in abatement of CO_2 as a function of total emission reduction. It can also be interpreted as the CO_2 cost at which applying additional reduction measures results in zero net present value (NPV) due to the saved CO_2 cost. MACC is a useful tool for both policymakers and shipowners to understand the cost of reducing emissions and to analyse the impact of policy measures, in particular economical elements which impose a price on CO_2 or GHG emissions. MACC has historically been used as input to policy processes in the IMO (Faber et al., 2020; Smith et al., 2014), and in the EU (Lindstad et al., 2015), and it is also directly referenced as a tool in IMO's GHG Strategy (IMO, 2023).

The first MACCs for shipping were published a decade ago and included technical and operational energy efficiency measures and LNG as fuel (Lindstad et al., 2015; Smith et al., 2014; Eide et al., 2013; 2011, 2009; Longva et al., 2010; Wang et al., 2010). Since then, we have seen further advancements of technologies and on the uptake of energy efficiency technologies, LNG and methanol as fuel and battery-powered ships (AFI, 2022). Other alternative fuels such as hydrogen and ammonia are also starting to emerge which, if produced sustainable, are needed to achieve full decarbonisation. There is an increasing number of papers reporting on abatement options for ships, including energy efficiency and alternative fuels (Jaramillo Jimenez et al., 2022; Dankwa Ampah et al., 2021; Romano and Yang, 2021). In particular, in the grey literature there are extensive reports which projects fuel and technology costs and impacts towards 2050 (Ricardo and DNV, 2023; DNV, 2022; MMMCZCS, 2021; LR and UMAS, 2020). There is, however, limited recent literature providing global MACCs taking into account the latest fuels, technologies and cost development (Martin et al., 2023; Nepomuceno de Oliveira et al., 2022; Irena et al., 2021; Schwartz et al., 2020; Smith, 2020; Faber et al., 2020; Hu et al., 2019;). There are also studies using other methods to report costs which can be compared with MACCs, such as Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS, 2021) and Baresic et al. (2022) who calculate a required CO_2 price to reduce GHG emissions to zero, and Mundaca et al. (2021) and Parry et al.(2018) use historical price elasticities to estimate the impact of changes in bunker fuel prices on CO_2 emissions.

In this paper, we present updated MACCs for 2030, 2040 and 2050 based on a systematic review by domain experts of cost and reduction potentials of more than 50 state-of-the-art energy efficiency measures, 8 alternative fuels and 10 fuel systems. The assessment is based on information from publicly available sources, communication with industry actors, and knowledge accumulated through more than 100 consultancy projects aiming to improve energy efficiency and reduce GHG emissions of ship fleets. This represents a significant improvement compared to previous MACC studies both in terms of measures included and providing an up-to-date evaluation of applicability and costs.

We have also seen an increase in the availability of detailed technical and operational data on individual ship level, such as AIS (Automatic Identification System) position data, IMO's mandatory fuel consumption reporting system (DCS – Data Collection System), and the EU's equivalent Monitoring Reporting and Verification (MRV) system. Improved modelling capabilities allow for taking such data into account, enabling more detailed and precise MACCs. We take advantage of enhanced modelling capabilities and data availability on technical and operational characteristics to develop MACCs for individual ships before aggregating them to fleet-level MACCs.

In this paper, we first provide the method and data sources for developing a MACC for shipping (section 2). We then present the results (section 3) including a sensitivity analysis. This is followed by a discussion of key uncertainties, a comparison with other studies and policy implications (section 4), before ending with concluding remarks (section 5). Key inputs and assumptions to our modelling are further described in the Appendix.

2. Method

The MACCs are developed in this study by combining activity-based, ship-specific emission modelling using operational profiles from AIS (Automatic identification System), with a comprehensive list of CO_2 emission reduction measures and associated costs. The method for producing MACC builds on that in Eide et al. (2011) but takes advantage of significant improvements in data availability and modelling. These improvements enable the production of a fleet-wide MACC based on ship-specific evaluations rather than on segment averages. Input data have been updated using state-of-the-art knowledge on the cost and effectiveness of abatement solutions, in particular alternative fuels.

The method to develop a MACC consists of three steps as illustrated in Fig. 1:

[2] Carbon-neutral fuels is used throughout this paper to denote fuels with limited or net-zero CO_2 emissions in a well-to-wake perspective. See http://www.ipcc.ch/sr15/chapter/glossary/

1. AIS data combined with fleet data are used to develop an activity-based technical and operational profile for each ship in the world fleet including a CO_2 emission baseline for the reference year 2019.
2. The future fleet is modelled year-by-year from 2020 to 2050 taking into account projected growth in transport demand. For each ship in the future fleet, the cost and CO_2 reduction potential of all available abatement options are evaluated.
3. Based on the cost and CO_2 reduction potential of available measures, a MACC is calculated for each ship in the future fleet and then aggregated into a fleet-wide MACC for 2030, 2040 and 2050.

In the following sections we describe the methods and models applied in each step and input data sources.

2.1. Step 1: AIS-based baseline

The baseline fleet CO_2 emission for 2019 is calculated using DNV's MASTER model (Mapping of Ship Tracks, Emissions and Reduction potentials). MASTER uses global ship-tracking data from AIS, enriched with ship-specific data from other sources, to on a daily basis model baseline fuel consumption and emissions for individual ships (Mjelde et al., 2019; 2014).

AIS data provide a detailed and high-resolution overview of current sailing speeds, operating patterns, sailed distances (nautical miles) and time spent at sea and in port by each vessel. The information from AIS is combined with technical data from IHS Markit and Alternative Fuels Insight (AFI, 2022; IHS, 2022) for detailed information on the individual ships, such as installed power on main and auxiliary engines, machine configuration, specific fuel consumption, ship design speed, deadweight tonnage, fuel type, and so on. These data form the basis for calculating fuel consumption and emissions and provide the operational characteristics for individual ships, with breakdown on operation modes such as transit, maneuvering and in port, which is used in this study as input for Step 2

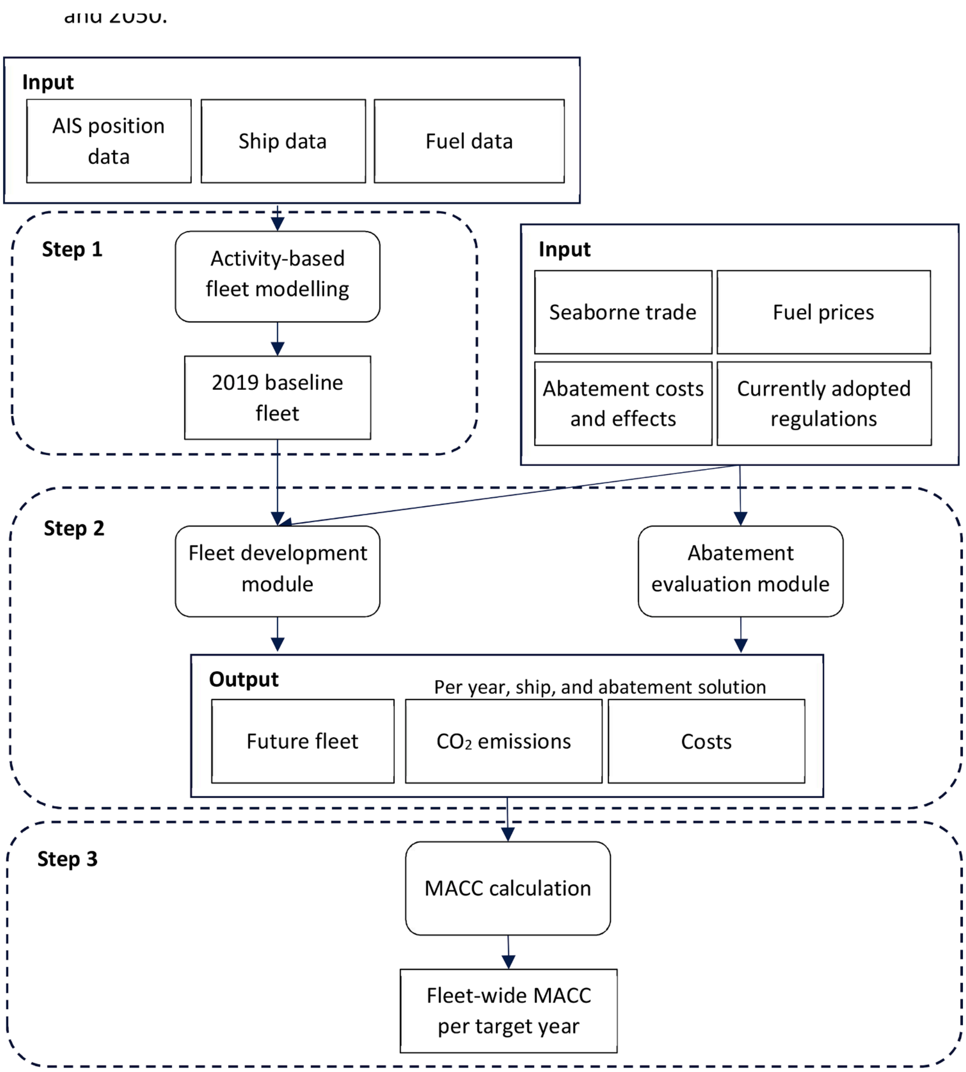

Fig. 1. The three steps applied to develop MACC. Rounded rectangles are process steps, while sharp cornered rectangles are inputs and outputs.

described below.

The baseline used in this study includes all ships above 400 gross tons, which is the threshold used in MARPOL Annex VI, Chapter 4, for regulations related to CO_2 emissions. Although an international regulation will exclude ships solely trading domestically, we do not distinguish between ships trading internationally and ships trading domestically.

2019 is used as a baseline year which was the last complete year before COVID. COVID severely disrupted trading pattern meaning that 2020 and 2021 would not provide representative operational profiles and CO_2 emissions for the ships in the fleet. Compared with CO_2 emissions reported through IMO's Data Collection System (DCS) in 2019, the model deviation is estimated to be below 5 % for a sufficiently large number of ships, although for individual ships it could be higher (Longva and Sekkesæter, 2021). There are 63 600 ships in the 2019 baseline meaning that the impact on the fleet level of any anomalies on individual ships is small.

Only CO_2 emissions are included in this study – that is, we exclude methane and other non-CO_2 GHG emissions. The impact of this is assessed in the sensitivity analysis. Upstream 'well-to-tank' emissions related to the production of fuels are also not included, although we assume that future non-fossil fuels are carbon-neutral.

2.2. Step 2: Fleet and abatement cost modelling

The fleet, abatement potential and costs have been modelled to 2050 using the GHG Pathway Model, a cost-based modelling tool, implemented in Python, for developing scenarios for decarbonisation of shipping (DNV, 2022; Longva and Sekkesæter, 2021; Eide et al., 2013; 2011). The Pathway Model is used for projecting a future fleet and to evaluate the cost and CO_2 reduction potential of all available measures for each ship in the future fleet. The model consists of a fleet development module and an abatement evaluation module (see Step 2 in Fig. 1). The fleet development module simulates scrapping and ship newbuilding year-by-year to 2050 with the objective that each segment can fulfil a given transport demand projection. The abatement evaluation module calculates the NPV and CO_2 reduction of abatement measures for each ship in the fleet and applies the compliant measure with highest NPV.

When applying different speed-reduction levels, fuel systems and energy-efficiency measures, the combined effect may not be the sum of the isolated effects of individual measures. To take into account the interaction between measures, they are considered in packages and groups. More than 50 detailed energy-efficiency measures are first packaged based on maturity (see Appendix for more details). Then measures are grouped together, each group consisting of a package of energy-efficiency measures, a speed reduction level, a fuel system and a fuel (see Table 1). The combined total emission reduction effect of the measures in the group can then be calculated for each individual ship. Each group is mutually exclusive to the others and only one can be implemented on the ship at any time.

A couple of emerging possible solutions are not included: the use of onboard nuclear reactors and onboard carbon capture and (subsequent) storage (CCS). These solutions are currently not technically mature enough to be taken up in significant numbers and questions remain about acceptance of nuclear technologies and regarding onshore infrastructure required for CO_2 reception and storage (DNV, 2022).

For each newbuild, the model evaluates all available combinations of energy-efficiency packages, speed reductions, fuel systems and fuels listed in Table 1. A ship can, for example, be equipped with the advanced energy-efficiency package + 10 % speed reduction + internal combustion engine (ICE) running on very low sulfur oil (VLSFO) or marine gas oil (MGO). A similar evaluation is made for all existing ships. For simplicity, existing ships cannot change their energy-efficiency package, i.e. the energy-efficiency measures selected at newbuild stage are kept throughout the lifetime of the vessel. Possible measures are further speed reduction and conversion of fuel system (converter and fuel) or switching fuel (drop-in fuel on existing converter). Building on the above example the existing ship could then be equipped with the advanced energy-efficiency package + 20 % speed reduction + retrofitted dual-fuel ICE running on LNG.

All NPV and emission reduction evaluations for the ships in existence in the fleet from 2020 to 2050 are used for the purpose of calculating the MACC in Step 3 (see section 2.3). The NPV and emission reduction for newbuilds are calculated relative to the ship without any reduction measures applied – i.e. the baseline or basic energy-efficiency package + 0 % speed reduction + ICE running on VLSFO or MGO. For existing ships, the calculation is performed relative to the measure group compliant with current polices that has the lowest NPV applied at the newbuild stage.

The initial supply of carbon-neutral fuels in 2030 is likely to limited before production can be scaled up towards 2040 and 2050 (Ricardo and DNV, 2023). IEA (2021) in their net-zero scenario projects that around 17 % of the energy supply to shipping is carbon-neutral in 2030, increasing to almost 60 % in 2040. The restricted availability is reflected in the MACCs for 2030 and 2040 where the potential CO_2 emission reductions from carbon-neutral fuels are limited based on IEA's projections.

The projection of a total seaborne trade in 2050 of about 80 trillion tonne-miles in this study (DNV, 2022) compares with the OECD_RCP2.6_G scenario in the Fourth IMO GHG study (Faber et al., 2020) with about 82.5 trillion tonne-miles. The input on energy-efficiency costs and reduction effects are based on DNV's Abatement Insight database covering cost and emission reduction potential for more than 50 technical and operational measures for different ship types and sizes. The data are based on domain expert assessment of information from literature (e.g. Faber et al., 2020; Bouman et al., 2017; Smith et al., 2014); more than 100 energy management consultancy projects; fuel consumption data from ship reports; DNV's Technology Outlook activities (DNV, 2022); and COSSMOS[3] modelling and simulation projects (Dimopoulos et al., 2020, 2016; 2014; Stefanatos et al., 2015).

[3] DNV COSSMOS (Complex Ship Systems Modelling and Simulation) is a computer platform that models, simulates and optimizes complex and integrated ship machinery systems with respect to energy efficiency, emissions, costs and safety.

Table 1
CO_2 abatement measures considered in the MACC. A 'measure group' will consist of one measure from each column with restrictions on certain combination energy-efficiency packages, fuel systems and fuels.

Energy efficiency package	Speed reduction	Fuel systems	Fuels
Baseline EE	0 %	MGO ICE	HFO (fossil)
Basic EE	10 %	HFO ICE+scrubber	VLSFO/MGO (fossil, e-, bio-)
Enhanced EE	20 %	DF LNG ICE	LNG (fossil, e-, bio-)
Advanced EE	30 %	DF LPG ICE	LPG (fossil)
Cutting-edge EE	50 %	DF Methanol ICE	Liquid hydrogen (e-, blue)
		DF Ammonia ICE	Methanol (e-, bio-)
		DF Hydrogen ICE	Ammonia (e-, blue)
		Hydrogen FC	Electricity
		Ammonia FC	
		EM Battery	

Key: sustainable biofuel (**bio-**); fuel produced from fossil energy with carbon capture and storage (**blue**); dual-fuel (**DF**); electrofuel (**e-**) made from renewable electricity; energy-efficiency (**EE**); electrical motor (**EM**); fuel cell (**FC**); internal combustion engine (**ICE**); heavy fuel oil (**HFO**); liquefied natural gas (**LNG**); liquefied petroleum gas (**LPG**); marine gas oil (**MGO**); very low sulphur fuel oil (**VLSFO**).

Estimated cost data for 8 energy converters and fuel systems are based on communication with industry actors, reported newbuild prices for vessels running on alternative fuels (AFI, 2022; IHS, 2022), and relevant literature (e.g. Kim et al., 2020 ; de Vries, 2019; Taljegard et al., 2014).

Fuel prices for fossil fuels used in the modelling are based on the historical relationship between bunkering prices and crude oil and natural gas prices, coupled with future projections of crude oil and natural gas prices (DNV, 2022). For carbon-neutral fuels evaluated, prices have been constructed using the levelized cost of production and distribution as proxy. Bottom-up costs are estimated per carbon-neutral fuel supply chain, including production and processing steps; distribution; and cost of CO_2 feedstock (as applicable), based on literature (e.g. Nelissen et al., 2020; Brynolf et al., 2018).

Further details on the GHG Pathway Model and input data are provided in the Appendix.

2.3. Step 3: marginal abatement cost curves

The final step is to calculate a MACC for each ship in the future fleet for a specific year. The MACCs for each ship are then aggregated into a fleet-wide MACC. All available measure groups evaluated in Step 2 for each ship in the future fleet are candidates for inclusion in the MACC.

A MACC is developed for three target years: 2030, 2040 and 2050. For each target year the fleet will consist of ships built in the preceding 30 to 40 years. The measure groups to be evaluated for inclusion in the ship-specific MACC will consist of the available retrofit and fuel drop-in options for the ship in the target year; and all available abatement options at newbuilding stage using the fuel prices of the target year. For ships built before 2019, the starting year in our modelling, only retrofit and fuel drop-in options are available. Thus, the MACC depicts the reduction opportunity space available to us if we start implementing measures *today*.

To calculate the MACC for each ship we start with the list of mutually exclusive applicable measure groups (*mg*). Each measure group has a net present value (*NPV*) and CO_2 reduction potential (*RED*) over the investment horizon (see Appendix for details on the NPV calculation). *NPV* and *RED* are relative to the baseline or basic energy-efficiency package, no speed reduction, and a conventional VLSFO/MGO diesel engine (see Table 1 and the Appendix for details on these groups). The marginal abatement cost (*MAC*) in USD per tonne CO_2 reduced for the *mg,* is calculated according to Eq. (1) for each ship by iterating through the available *mg* in the following steps:

1. The *mg* with the highest *NPV* is added to the MACC as the first *mg*
2. Disregard all *mg* with lower or equal *RED* than the recently added *mg* in further evaluations
3. For all *mg* with higher RED than the recently added *mg*, recalculate MAC_{mg} according to Eq. (1) relative to the most recently added *mg*
4. The *mg* with the lowest *MAC* is added to the MACC as the next *mg*
5. Repeat from step 2 above until no *mg* with higher *RED* (i.e. 100 % reduction) are left

$$MAC_{mg} = \frac{-\Delta NPV_{mg}}{\Delta RED_{mg}} \tag{1}$$

The result is a ship-specific MACC which consists of a list of *mg* each with a *MAC* relative to a previous *mg* with lower *MAC* and lower *RED*.

The final step is to calculate the fleet-wide MACC, which is the maximum CO_2 reduction achieved for the total fleet, RED_{fleet}, as a function of *MAC*. The impact of speed reduction needs to be taken into account explicitly at the fleet level as the reduction calculated for a specific *mg* applies to an individual ship. But in case of reduced speed and transport capacity, additional ships need to be built, which increases CO_2 emissions from other ships. We assume that the need for new capacity is proportional to the reduction in distance sailed – e.g. a 10 % speed reduction leads to a 10 % reduction in distance sailed, which needs to be replaced by a ship with similar CO_2 emissions (i.e. having the same measure group applied). The adjusted CO_2 emission reduction (RED_{adj}) in tonnes CO_2 after applying a speed reduction (SR_{rel} – expressed as% of previous speed) can be calculated based on emission before (E_{prev}) and after (E_{new}) applying the speed reduction according to Eq. (2) as follows:

$$RED_{mg,\ adj} = E_{prev} - E_{new} + E_{new} \times \frac{1}{1 - SR_{rel}} \tag{2}$$

Note that the MAC remains unchanged even with the adjusted CO_2 reduction as the MAC is seen from the shipowner perspective and not from the fleet level.

The fleet-wide MACC can then be established, selecting for each ship the *mg* with the highest adjusted CO_2 reduction where MAC_{mg} is lower than *MAC*. The CO_2 reduction for the fleet (RED_{fleet}) is then the sum of the reduction for each ship as shown in Eq. (3).

$$RED_{fleet}(MAC) = \sum_{ship} \max\left(RED_{mg,adj}\right) \ where \ MAC_{mg} < MAC \tag{3}$$

3. Results

In the following we present the calculated MACCs for 2030, 2040 and 2050. Then we project the resulting fleet CO_2 emission level if applying all measures below a certain marginal abatement cost. Finally, we provide a sensitivity analysis considering key input data and assumptions impacting our results.

3.1. Marginal abatement cost curves

The baseline CO_2 emission levels for the future fleet, with no abatement measures or speed reductions applied, rises from 1090 $MtCO_2$ in 2030 to 1301 $MtCO_2$ in 2040, and finally to 1394 $MtCO_2$ in 2050 as the projected seaborne trade and shipping fleet activity increases.

MACCs for 2030, 2040 and 2050 are shown in Fig. 2 with the marginal abatement cost on the x-axis and the fleet CO_2 emission level on the y-axis. The fleet CO_2 emission level is the remaining emissions after implementing all measures up to the marginal cost. The baseline emission levels given above correspond to the leftmost point in the curves where no measures are applied.

Across the years, we find that the reductions up to a marginal abatement cost of about 200 USD/tCO_2 can be achieved by energy-efficiency and speed-reduction measures, and LNG as fuel. These measures cannot by themselves reduce the emissions to zero, and the fleet CO_2 level reaches a plateau around 600–700 $MtCO_2$. In 2030, this amount to only 40 % reduction from the baseline level, but increases to almost 60 % reduction 2050, due to a larger amount of more energy efficient ship entering the fleet before 2050. Beyond this level, further reductions down to zero must come from application of carbon-neutral fuels, with a marginal abatement cost of up to 330 USD/tCO_2 in 2050. Carbon-neutral fuels are not expected to be available in sufficient quantities and the reduction potential is limited beyond reaching a CO_2 emission level of about 400 Mt in 2030 and 200 Mt in 2040.

Initially the fleet consists of ships sailing today with limited options for reducing emissions. We assume in our modelling that new

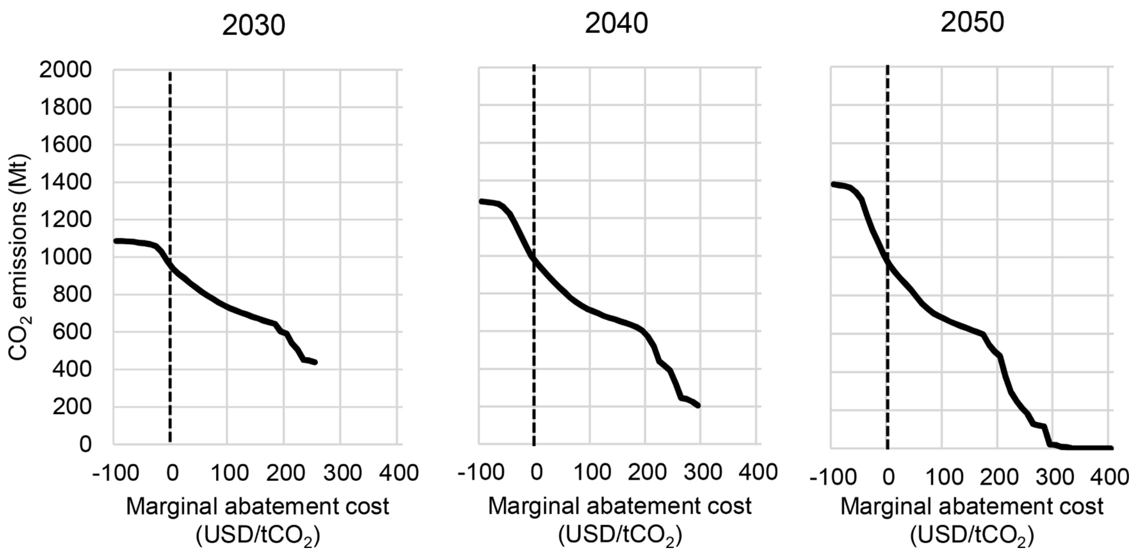

Fig. 2. MACCs for 2030 (left), 2040 (middle) and 2050 (right). Note that the supply of carbon-neutral fuels is not expected to be sufficient to reach zero emissions in 2030 and 2040.

ships can make more optimal design choices, for example by choosing a more energy-efficient design and a dual-fuel ammonia or methanol engine as the carbon-neutral versions of these fuels are expected to have a lower price. This can be seen in the MACC for 2050 where the marked bend in the curve comes at a lower marginal abatement cost than the previous years.

Shipping MACCs can be used as an indication of how high CO_2 price shipowners are willing to pay, all else being equal, before implementing further measures to reduce CO_2 emission on their ships. If shipowners only implement measures with a marginal abatement cost below zero – i.e. having a positive NPV without any additional CO_2 price – the CO_2 emission level stays around 950 Mt CO_2. This does not take into account other requirements such as the current EEDI, EEXI and CII regulations which may force the implementation of measures with marginal abatement cost above zero. A 20–30 % CO_2 emission reduction in 2030 relative to 2008, can be achieved at a marginal cost of about 50–100 USD/tCO_2 in 2050. Up to this level, changes in marginal abatement cost result in only small changes in the emission level. Above 200 USD/tCO_2 the measures start to include carbon-neutral fuels which are needed to reduce CO_2 emissions to zero by 2050. To achieve 70–80 % emission reduction in 2040, the marginal cost will be around 230–240 USD/tCO_2 and zero CO_2 emissions in 2050 can be reached at a marginal cost of 300 USD/tCO_2.

Fig. 3 shows the estimated CO_2 emission level by applying all measures below a given MAC for each ship. This can be interpreted as the resulting CO_2 level assuming a constant CO_2 price equal to the marginal abatement cost imposed on the shipowners between now and 2050. The price must be imposed throughout the period to ensure ships are fitted with the most optimal measures at newbuild stage. The chart also indicates the emission trajectories consistent with the ambitions in the revised IMO GHG strategy, relative to a CO_2 emission of 923 Mt in 2008 (Smith et al., 2014).

3.2. Sensitivity analysis

The results presented above are based on our central estimates of abatement costs and reduction potential. The wide range of assumptions are inherently uncertain. The aim of the sensitivity analysis is to investigate how the method and modelling respond to changes to key inputs and assumptions, and the relative importance of the various inputs. The uncertainty of the results is then discussed in light of the sensitivity analysis. We assess the sensitivity by systematically changing one parameter at a time. The changes in the parameters should be in the lower or upper end of an expected range, but not reflect the extreme range of possibilities. We also provide high and low estimates where all the changes resulting in increased or reduced marginal abatement cost respectively are combined.

Table 2 shows the results of the sensitivity analysis with relative changes to the fleet CO_2 emission levels at a marginal abatement cost of 0 and 100 USD/tCO_2, and relative changes to the marginal abatement cost for 450 and 0 MtCO_2 emission levels, resulting from changes to key inputs and assumptions. These measure points are representative for initial emission reductions, and for a 50 % and 100 % emission reduction. All numbers are relative to the base scenario in 2050.

Fig. 4 shows the fleet MACCs with the high and low estimate for 2030, 2040 and 2050. The spread is large but dominated by the uncertainty on fleet growth and carbon-neutral fuel costs. A high fleet growth increases the resulting emission levels at 100 USD/tCO_2 by 10 % in 2030 and 90 % in 2050, reflecting that each ship needs to reduce CO_2 emissions more at higher marginal costs to achieve the same emission level as for a lower growth scenario. However, the marginal cost needed to reach zero emissions is the same, as this is independent of the number of ships in the fleet.

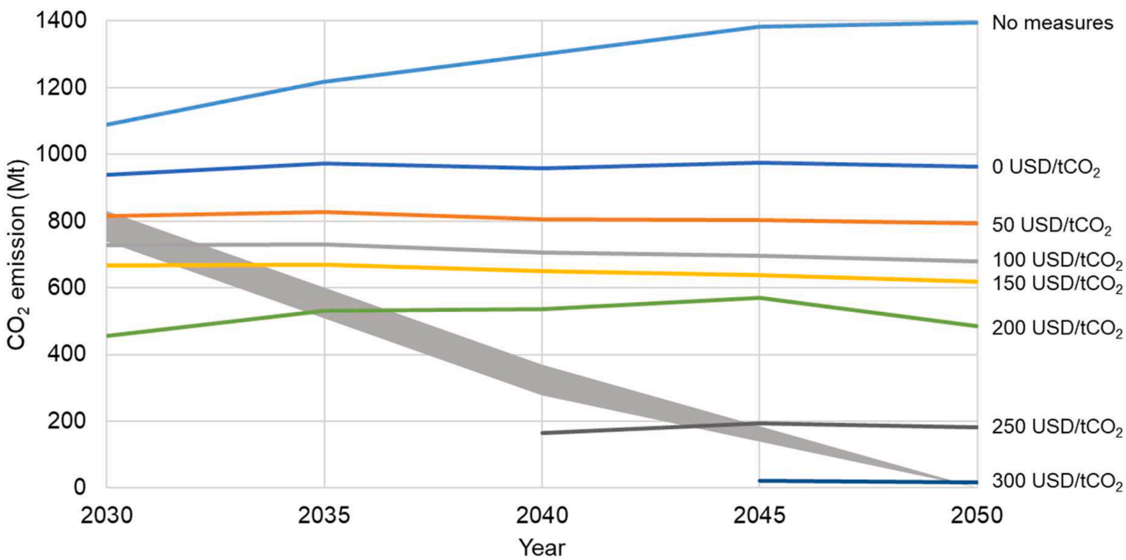

Fig. 3. Emission trajectories by applying all abatement measures below a given marginal abatement cost, and baseline trajectories (no measures). The trajectories are interpolated between 2030, 2040 and 2050. The grey area indicates the ambitions in the revised IMO GHG Strategy relative to the 2008 CO_2 emissions. Note that the supply of carbon-neutral fuels is not expected to be sufficient to achieve zero emissions until well after 2030.

The carbon-neutral fuels costs do not have a high impact on the emission levels at marginal costs up to 100 USD/tCO_2 as these levels are achieved by energy efficiency, speed reduction, and using LNG as fuel. The largest impact is on the marginal costs to achieve zero CO_2 emissions, where $a \pm 25$ % change in carbon-neutral fuel costs lead to $a \pm 33$ % corresponding change in marginal costs. The reason for the higher percentage is that a 25 % increase in absolute cost of carbon-neutral fuels leads to a greater increase in the relative costs between fossil and carbon-neutral fuels, which is the main determining factor for the marginal costs.

4. Discussion

This section starts with a discussion of uncertainties and limitations before comparing the results with other estimates of marginal abatement costs and CO_2 prices. Finally, we comment on implications for policy makers and shipowners.

4.1. Uncertainties and limitations

Based on the sensitivity analysis we find that the two inputs which have the highest impact on the results are the future cost of carbon-neutral fuels and growth in seaborne trade.

The main determinants of the cost of future carbon-neutral fuels are expected to be the cost and availability of key input factors such as sustainable biomass, renewable electricity, and carbon capture technologies, including infrastructure for storing the captured carbon (DNV, 2022). These in turn are highly dependent on the global energy supply. Looking at other fuel price estimates (MMMCZCS, 2024; Soler et al., 2022; IRENA, 2021; LR and UMAS, 2020; IEA, 2019) we see a large variation with fuel prices ranging from 35 % below our estimates up to 60 %, and in some cases 100 %, above them. Regarding availability, in the early stages carbon-neutral fuels are likely to be specifically sourced, while over time a global infrastructure needs to be built up to supply these fuels to ships. In this transition, shipowners will face difficult decisions on engine and fuel systems, taking into account trading area, expected availability of the fuel, and regulations including a future CO_2 price.

The MACCs presented in this paper only covers CO_2 emissions which currently accounts for 98 % of GHG emission from shipping (Faber et al., 2020). The EU ETS and FuelEU Maritime regulations will take into account methane (CH_4) and nitrous oxide (N_2O) emissions (EU, 2023a, 2023b). It is also expected that the IMO will address CH_4 and N_2O emissions for upcoming regulatory measures according to the ambitions stated in the revised GHG strategy (IMO, 2023).

The growth in seaborne trade demand poses a significant uncertainty for the marginal abatement cost of reaching intermediate emission reduction levels. With a larger fleet and greater activity each ship needs to reduce relatively more to reach the same CO_2 emission level compared with a lower growth and activity level. This will increase the total cost of reducing emissions from shipping but does not affect the marginal abatement costs to achieve zero CO_2 emission where all ships need to reduce to zero.

The MACCs presented here are based on financial NPV calculations which do not cover all aspects of an investment decision. There are other barriers and drivers that will impact the cost and uptake of reduction measures (Hellström et al., 2024; Nepomuceno de Oliveira et al., 2022; Psaraftis et al., 2021; Rehmatulla and Smith, 2015, 2020; ITF/OECD, 2018). One example is the split-incentives barrier where shipowners that need to provide investments do not see the fuel-saving benefits and. Another, as mentioned above, is the availability of alternative fuels, which is expected to be a significant barrier for investing in specific dual-fuel solutions such as

Table 2
Sensitivity analysis showing relative changes to the fleet CO2 emission levels at a marginal abatement cost of 0 and 100 USD/tCO2, and relative changes to the marginal abatement cost for 450 and 0 MtCO2 emissions, resulting from changes to key inputs and assumptions. All numbers are relative to the base scenario in 2050 as presented in Section 3.1.

	0 USD/tCO_2	100 USD/tCO_2	450 MtCO_2	0 MtCO_2
Base scenario 2050	*963 Mt*	*679 Mt*	*210 USD/tCO_2*	*330 USD/tCO_2*
Carbon-neutral fuels cost −25 %	−1 %	−2 %	−38 %	−33 %
Carbon-neutral fuels cost +25 %	0 %	0 %	38 %	33 %
Fossil LNG cost +25 %	12 %	4 %	−10 %	0 %
Ammonia and methanol engines and fuel systems CapEx −25 %	0 %	0 %	−10 %	0 %
Ammonia and methanol engines and fuel systems Capex +25 %	0 %	0 %	5 %	0 %
Energy-efficiency measures CapEx −25 %	−1 %	0 %	0 %	0 %
Energy-efficiency measures CapEx +25 %	1 %	0 %	0 %	0 %
Speed-reduction opportunity cost −25 %	−8 %	−6 %	0 %	0 %
Speed-reduction opportunity cost +25 %	6 %	11 %	0 %	0 %
Speed-reduction impact – more time at sea (50 % replacement)	0 %	−8 %	−10 %	0 %
High growth +1.8 pp (3.0 % per annum)	92 %	90 %	14 %	0 %
Long investment horizon (20 years)	−14 %	−7 %	−14 %	0 %
Including methane slip (+0.356 down to +0.044 CO_2 emission factor for all LNG fuels)	3 %	1 %	0 %	0 %
Low estimate[3]	**−16 %**	**−51 %**	**−52 %**	**−33 %**
High estimate[4]	**123 %**	**114 %**	**62 %**	**33 %**

[3] Combining: Carbon-neutral fuels cost −25 %; Ammonia and methanol engines CapEx −25 %; Energy efficiency measures cost −25 %; Speed reduction opportunity cost −25%; Speed reduction impact – more time at sea (50 % replacement); and Long investment horizon (10 years).

[4] Combining: Carbon-neutral fuels cost +25 %; Fossil LNG cost +25 %; Ammonia and methanol engines CapEx +25 %; Energy efficiency measures cost +25 %; Speed reduction opportunity cost +25 %; High growth +1.8 pp (3.0 % p.a.); and Including methane slip (+0.356 down to +0.056 CO_2 emission factor for all LNG fuels).

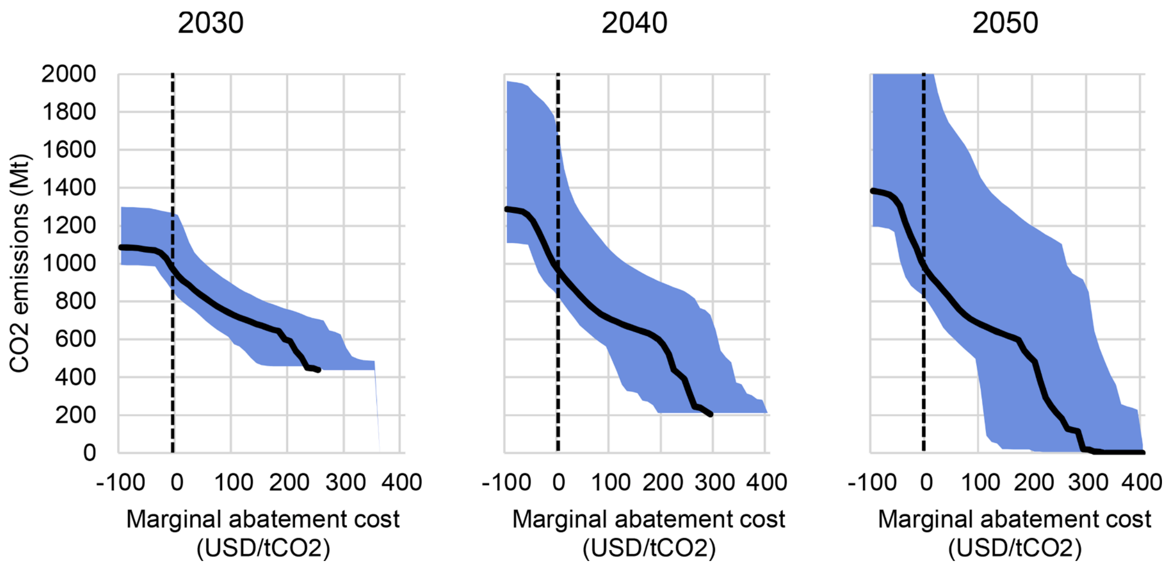

Fig. 4. Fleet MACCs including a high and low estimate for 2030, 2040 and 2050.

ammonia and methanol.

A CO_2 pricing mechanism, implemented for example by the IMO, can also impact the abatement costs by increasing the cost of using fossil fuels (Lagouvardou et al., 2022; Psaraftis et al., 2021). If the collected revenues from a pricing mechanism are redistributed to the maritime industry, for example by funding research and development of solutions, or by direct subsidies for investment costs or carbon-neutral fuels, this is likely to have a feedback effect on the MACC. Future technical requirements beyond the currently adopted EEDI, EEXI and CII – such as further strengthening the CII after 2030, or a well-to-wake GHG fuel standard – can also impact the MACC. Such technical requirements can for example mandate implementation of expensive carbon-neutral fuels. This will increase the fuel cost for ships, which will increase cost savings from energy-efficiency and speed-reduction measures, resulting in a lower marginal abatement cost for these measures.

4.2. Comparison with other studies

We have compared our results with other studies which estimate CO_2 prices and resulting CO_2 emission levels, looking in particular at three methods: MACC as applied in this study, fleet modelling, and using historical price elasticities. It is beyond the scope of this paper to do a detailed comparison of the methods, assumptions and inputs, and only key differences are highlighted here together with the main findings.

Eide et al. (2011) calculate a global MACC showing potential to reduce CO_2 emissions by 33 % and 49 % at marginal abatement costs of 0 USD/t and 100 USD/t, respectively, by 2030. The reduction is compared with a baseline emission of 1533 Mt. This is significantly higher than in this study which estimates a 14 % and 33 % reduction potential at marginal abatement costs of 0 USD/t and 100 USD/t, respectively. However, the baseline emissions in this study are only 1090 Mt due to lower seaborne trade growth rate, both historically between 2010 and 2020, and in future projections. Higher seaborne trade growth leads to a higher number of newbuilds with lower marginal abatement costs in the fleet. Another important difference is that Eide et al. (2011) models the potential implementation of measures in 2030, starting a decade earlier than our study, thus including a higher number of newbuilds with a wider scope of options to reduce emissions.

Smith (2020) presents MACCs for several scenarios with the marginal cost ranging from 100 to 500 USD/tCO_2 for 2050 due to variations in price and availability of fuels. The Fourth IMO GHG study (Faber et al., 2020) provides MACCs for 2030 and 2050 indicating that in 2030 emissions can be 30 % less than the baseline at a marginal cost of 258 USD/tCO_2, and that full decarbonisation can be reached in 2050 at 416 USD/tCO_2. Martin et al. (2023) estimate the levelized cost of carbon abatement for shipping fuels made from onshore wind or hydro power to between 167 and 393 EUR/tCO_2 in 2050. This compares with marginal costs of about 130 USD/tCO_2 and 330 USD/tCO_2 for the same reductions and target years in our study. The MACC in the Fourth IMO GHG study uses explicit measure penetration rates, which for alternative fuels without carbon (including biofuels) were set very low in 2030 (<0.1 %). The difference in 2030 can to some degree be explained by the price of LNG, which is 30 % to 40 % higher than in this study. For 2050, the estimated prices of carbon-neutral fuel prices in the Fourth IMO GHG study were 40 % to 60 % greater than here, which would explain the higher marginal abatement cost in the Fourth IMO GHG Study.

There are alternative approaches to estimate marginal abatement cost and emission levels. Based on fleet modelling, Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping (MMMCZCS, 2021) suggests that a flat 230 USD/tCO_2 levy imposed from 2025 will reduce well-to-wake GHG emissions to 250 MtCO_2e in 2050. This is similar to our estimate of 250 MtCO_2 at a marginal cost of 230 USD/tCO_2, though we only include tank-to-wake emission and only address carbon dioxide. Baresic et al. (2022) present a required

CO_2 price trajectory for full decarbonisation by 2050. This trajectory is close to 100 USD/tCO_2 in 2030, 230–260 USD/tCO_2 between 2035 and 2045, increasing to around 360 USD/tCO_2 in 2050.

Mundaca et al. (2021) estimate that a 40 USD/tCO_2 carbon price will reduce CO_2 emissions by 18.2 % in 2030 and 28.8 % in 2050 relative to a business-as-usual projection for heavy products (e.g. oils, ores, grains). The paper uses historical price elasticities to estimate the impact of changes in bunker fuel prices on CO_2 emissions, and assumes no growth in seaborne trade to 2030 and 2050. The comparable reductions in our study for a marginal abatement cost of 50 USD/tCO_2 for the total fleet are 25 % in 2030 and 43 % in 2050, which is significantly higher. Parry et al. (2018) applies a similar method and investigates a scenario where the CO_2 price gradually increases to 75 USD/tCO_2 in 2030 and 150 USD/tCO_2 in 2040. The result was a 14 % reduction in CO_2 emissions in 2030, increasing to 23 % in 2040 relative to a business-as-usual scenario. This is approximately half the reduction potential estimated in this study. Schwartz et al. (2020) investigate the potential for operational and technical measures, resulting in a 50 % reduction in CO_2 emissions in 2050 at zero marginal cost, compared to a 31 % reduction in this study.

The MACC and fleet modelling studies provide bottom-up estimates based on the cost and reduction potential of specific studies and using financial calculations to estimate the response on uptake in the fleet. Although there are large variations, the newer studies fall into the same order of magnitude with a marginal abatement cost around 300–420 USD/tCO_2 for a full decarbonisation by 2050. This span is mainly explained by variations in the fuel prices used in the studies. Extrapolating historical price elasticities to predict future responses is only valid for modest price changes and reductions, as there is no experience on the response on adding a cost of 300–420 USD/tCO_2e corresponding to a 950–1350 USD/t fuel (VLSFO or MGO) increase.

4.3. Implications for policymakers and shipowners

MACC is a useful tool to analyse the impact of policy measures, and in particular regulations with economical elements that price CO_2 or GHG emissions. From 1 January 2024 shipping is included in the cross-sector EU Emission Trading System which sets a price on CO_2 emissions through a limited auctioning of allowances (EU, 2023b). The IMO is considering a basket of measures with technical and economical elements. These measures, if adopted in 2025, can take effect from 2027 (IMO, 2023). In a policy context, MACC can be used to estimate an expected emission level given a set CO_2 cost. In a flexibility mechanism where ships can pool compliance, such as for FuelEU Maritime, there is no explicit CO_2 price, but ships participating in a pool may still make financial settlements where the ships that reduces the GHG intensity is compensated by the ships not implementing any measures. Marginal abatement costs can be used to assess the cost impact for shipowners for such a mechanism. Shipowners should develop decarbonisation strategies as well as specific MACCs for their ships and fleets. The MACC can support decisions on which measures to include in the ship operational carbon intensity plans which have to be included in their SEEMP.

In the short term, growth in seaborne trade and LNG prices are the two factors which impact the marginal cost and related emission levels up to about 50 % reduction. In the long-term, uncertainty over the price and availability of carbon-neutral fuels is the most significant factor. This poses a challenge for policymakers when deciding on MBMs. A pre-determined CO_2 levy may not be sufficiently high to incentivise production and uptake of carbon-neutral fuels. This uncertainty prevails even if reviewing and updating the levy as often as every five years. A CO_2 price determined by the market through a cap-and-trade system should exactly cover this price gap, but the exact price level cannot be determined before the allowances are actually traded. For shipowners, both approaches create uncertainty which must be addressed by policymakers.

Policymakers should ensure that any economical element establishes a predictable, continuous and sufficiently high CO_2 price. This ensures that the most optimal choice can be taken at newbuild stage. For example, if a ship is built with dual-fuel ammonia engines it can run on an expected cheaper fuel rather than switching to a bio- or e-MGO. It is also important to ensure a predictable and reliable CO_2 price to incentivise production and infrastructure development for carbon-neutral fuels.

5. Conclusion

This study presents the most detailed marginal abatement cost curves (MACCs) to date for all ships above 400 GT from 2025 to 2050. It is based on individual ships' technical and operational characteristics and CO_2 emission abatement costs, and on effectiveness data for more than 50 state-of-the-art measures, 10 fuel systems and 8 fuel types. The revised IMO GHG strategy ambition of 20–30 % GHG emission reduction in 2030, relative to 2008, can be reached at a marginal cost of 50–100 USD/tCO_2; 70–80 % emission reduction in 2040 can be achieved at 230–240 USD/tCO_2 and net-zero emissions in 2050 at a marginal cost of 300 USD/tCO_2. These estimates are in the low end of the range of estimates by other studies reporting a marginal abatement cost of around 300–420 USD/tCO_2 for a full decarbonisation by 2050.

The future cost of carbon-neutral fuels is the input factor with the highest sensitivity and uncertainty for the MACC results. This is also reported as a critical factor by other studies in the literature. The main determinant is expected to be the availability of key input factors such as sustainable biomass, renewable electricity, and carbon capture technologies, including infrastructure for storage. A sensitivity analysis showed that a 25 % increase or decrease in the cost of carbon-neutral fuels resulted in a corresponding 33 % change in the marginal abatement cost for achieving zero CO_2 emissions in 2050. The growth in seaborne trade demand poses a significant uncertainty for the intermediate reduction levels before reaching zero emissions. With a larger fleet and activity, each ship needs to reduce emissions relatively more to reach the same CO_2 emission level. However, this does not affect the marginal abatement costs to achieve zero CO_2 emission as all ships need to reduce to zero regardless of the growth in activity.

MACC is an important tool to assess the impact of decarbonisation ambitions and regulatory measures. This is highly relevant in relation to current discussion in the IMO on further regulatory measures with both technical and economical elements. Policymakers should ensure that any economical element establishes a predictable, continuous and sufficiently high CO_2 price closing the price gap between fossil and carbon-neutral fuels. The price can be explicit in case of a CO_2 levy or implicit in case of a pooling mechanism where ships can pool compliance. This ensures that the most optimal choice can be taken at newbuild stage and incentivises production and infrastructure development of carbon-neutral fuels. The MACC can support shipowners in developing decarbonisation strategies and deciding which measures to implement in their fleets, as well as support with deciding on joining a compliance pool.

CRediT authorship contribution statement

Tore Longva: Writing – original draft, Software, Methodology, Formal analysis, Conceptualization. **Magnus S. Eide:** Methodology, Writing – review & editing. **Øyvind Endresen:** Writing – review & editing, Methodology, Investigation. **Øyvind Sekkesæter:** Writing – review & editing, Investigation. **Henrik Helgesen:** Writing – review & editing, Software, Investigation, Formal analysis. **Nikolai Hydle Rivedal:** Writing – review & editing, Software, Investigation, Formal analysis.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix: Method description and Input data

In this appendix, we provide further details on calculations, key input and assumptions made in the modelling work.

Emission calculations

$$EM = \left(E_{Base,ME} \times \left(1 - R_{EE,\ ME}\right) \times \left(1 - R_{SR,\ ME}\right) + E_{Base,AE} \times \left(1 - R_{EE,AE}\right) + E_{Base,Boiler}\right) \times SFC \times C_f \tag{A1}$$

The CO_2 emission (EM), in grams, is calculated according to Equation A1. The ship's energy use (in MJ) is multiplied with the specific fuel consumption (SFC, in g fuel/MJ) of the converter, and the CO_2 emission factor (C_f, in gCO_2/gram fuel – see Table A6) of the fuel. The SFC is as an average set to 170 g/kWh for engine built prior to 2019, and decreasing to 155 g/kWh in 2050 based on engine build year. The energy use is derived from the base energy use (E_{Base}), calculated by the MASTER Model and split into main and auxiliary engines and boilers, and multiplied with the reduction effects (R, in%) of energy efficiency measures (see Table A4) and speed reductions. The reduction effect of speed reduction is estimated using the "Cubic Rule" method where the engine power increases with speed raised to the third power.

Cost calculations

The net present value (NPV_{mg}), in US dollars, is calculated according to Eq. (A2) for each available and compliant measure group (*mg*) based on the capital costs (*CapEx*) plus the operational cost (*OpEx*), lost opportunity cost (*SpeedLO*) related to speed reduction, and fuel cost (*FuelEx*), over a certain investment horizon period *p* with discount rate *r*:

$$NPV_{mg} = -\ CapEx - (OpEx + FuelEx + SpeedLO)\ \times \frac{1 - (1 + r)^{-p}}{r} \tag{A2}$$

Capital expenses include the additional cost of energy-efficiency measures, energy converter, fuel system and fuel-storage costs. Operational expenses include all additional costs of operating the equipment, while the fuel expenses include the additional or reduced fuel cost. The lost opportunity cost is an estimated cost to the shipowner of reducing speed. The costs are relative to a ship with baseline energy-efficiency measures, no speed reduction and a conventional VLSFO/MGO diesel engine. The discount rate *r* is set to 4 %.

Transport demand projection

The seaborne-trade demand is based on projections in DNV (2022) as provided in Table A1.

Table A1
Seaborne-trade demand growth assumption 2020–2050 (DNV, 2022).

Cargo type	Annual growth 2020–2030	Annual growth 2031–2040	Annual growth 2041–2050	Total growth 2020–2050
Bulk	1.5 %	0.9 %	−0.1 %	27 %
Liquid tank	0.5 %	−0.9 %	−1.3 %	−16 %
Gas	5.0 %	3.6 %	2.2 %	204 %
Container	3.0 %	1.7 %	1.5 %	91 %
Other cargo	2.3 %	1.2 %	1.0 %	60 %
Non-cargo	1.7 %	0.8 %	0.3 %	35 %
Total	**1.6 %**	**0.9 %**	**0.3 %**	**35 %**

Investment horizons

The perspective of the MACC is the shipowner's investment calculation where the horizon is usually shorter than in a societal perspective that would include the full lifetime of the vessels and measures. In the model, each vessel is randomly assigned a horizon (p) based on the distribution for its segment as shown in Table A2. This horizon remains the same for all measures applied by the ship ensuring an equal comparison of measures applicable for the ship. The investment horizon used when evaluating measures for existing ships is half the length as when evaluating for newbuilds, assuming that newbuild investments are more long term than subsequent investments (see e.g. Stott, 2013).

Table A2

Distribution of investment horizon for different segments for newbuilds (NB) and retrofits (RF) (Ricardo and DNV, 2023).

Segment	NB: $p = 4$ years RF: $p = 2$ years	NB: $p = 10$ years RF: $p = 5$ years	NB: $p = 20$ years RF: $p = 10$ years
Container and vehicle	20 %	60 %	20 %
Cruise	10 %	40 %	50 %
All other segments	30 %	60 %	10 %

Energy efficiency measures

The GHG Pathway Model does not evaluate the uptake of each single energy-efficiency measure (e.g. waste-heat recovery, air-cavity lubrication) due to the interactions between the measures. We instead compile the energy-efficiency (EE) measures into five internally consistent packages based on generation and maturity, as presented in Table A3. The measures included in the different EE packages will depend on the applicability for the ship type in question.

Table A3

Energy-efficiency (EE) packages used in the GHG Pathway Model (DNV, 2022).

Energy-efficiency package	Maturity	Measures included
Baseline EE	–2015	Average energy efficiency of a vessel built before 2015. Includes basic operational measures, as well as standard hull cleaning, propeller polishing, engine auto-tuning and optimisation of cargo handling systems.
Basic EE	2015–2020	Average energy efficiency of a vessel built after 2015 and until 2020. Includes hull form optimisation, basic machinery improvements, variable frequency drives, shaft motor/generator, and measures to improve hydrodynamic propulsion, such as devices before the propeller and high-efficiency propellers and rudders.
Enhanced EE	2020–2025	Energy-efficiency measures expected to be mature between 2020 and 2025. Includes batteries, waste-heat recovery systems, bow shapes optimised for real sea states, variable engine speed and improved steam-plant.
Advanced EE	2025–2030	Energy-efficiency measures expected to be mature between 2025 and 2030. Includes, among other measures, hard sails, solar panels, next-generation waste-heat recovery systems, and reduced-ballast design.
Cutting-edge EE	2030–	Measures expected to mature after 2030 are placed in the cutting-edge package, including digital twins and onboard wind turbines.

Based on the cost of individual measures in each EE package, a total CapEx and annual OpEx have been calculated. The cost and emission reduction effects are shown in Table A4 with ranges depending on ship segment. The cost of Basic EE is used as reference point, while Baseline EE are only used on existing ships and no cost evaluation is done.

Table A4

Additional cost and emission reduction effects of energy efficiency packages. The ranges reflect ship segment variations.

Energy-efficiency package	CapEx [MUSD]	OpEx [kUSD/year]	ME consumption reduction	AE consumption reduction
Baseline EE	N/A	N/A	–	–
Basic EE	Ref	Ref	9–10 %	2–4 %
Enhanced EE	0.3–1.2	3–33	9–24 %	5–8 %
Advanced EE	3.4–6.9	3–63	13–29 %	6–14 %
Cutting-edge EE	5.9–9.7	500–570	15–32 %	7–15 %

Key: auxiliary engines (AE); capital expenditure (CapEx); energy efficiency (EE); thousand US dollars (kUSD); main engines (ME); operational expenditure (OpEx); million US dollars (MUSD).

Fuel technologies

Fuel technology costs include the cost of energy converter and fuel-supply system in USD per kilowatt (kW) of installed power, and the cost of the fuel-storage system in USD per gigajoule (GJ) of energy storage capacity, which is a function of the vessel's design range. This approach inherently overestimates cost for vessels with very high installed power and fuel-storage capacity in certain segments, and underestimates cost for vessels with low installed power and fuel-storage capacity. To remedy this, we have added a fixed CapEx correction per ship segment. This correction constant, which can be negative or positive, was derived from comparing the reported

CapEx of newbuild vessels running on alternative fuels, and our estimates using unit costs (USD/kW and USD/GJ).

Table A5 shows the fuel technologies and associated additional costs for newbuilds evaluated in the GHG Pathway Model. Retrofitting to the specific fuel technology is assumed to cost an additional 50 %. We have not considered opportunity costs related to loss of cargo-space due to additional volume required for fuel storage, nor lost income during installation. Note that EM Battery will have negative cost for the converter (i.e. the electric motor) relative to a MF MGO ICE. The data is based on communication with industry actors, reported newbuild prices for vessels running on alternative fuels (AFI, 2022; IHS, 2022), and relevant literature (e.g. Kim et al., 2020; de Vries, 2019; Taljegard et al., 2014).

Table A5
Additional newbuild CapEx for fuel technologies, including converter, fuel system and fuel storage relative to a MF MGO ICE. The ranges for converter and storage reflect variation in installed power and storage capacity within segments, while the fixed correction reflects variations between ship segments.

FUEL TECHNOLOGY	CAPITAL EXPENDITURE		
	Correction [MUSD]	Converter & fuel system [USD/kW]	Storage [USD/GJ]
MF MGO ICE	*Ref*	*Ref*	*Ref*
MF HFO ICE + scrubber	0.6–1.5	129–194	0
DF LNG ICE	−10.0–5.0	420–490	62–120
DF LPG ICE	2.0–5.0	180–250	35–80
DF Methanol ICE	1.0–2.5	140–210	20–27
DF Ammonia ICE	−5.0–5.0	276–346	37–100
DF Hydrogen ICE	2.0–5.0	997–1192	157–320
Hydrogen FC	2.0–5.0	4891–4971	157–320
Ammonia FC	2.0–5.0	1655–1730	37–100
EM Battery	0	−90 to −10	45,000

Key: Capital expenditure (CapEx); dual-fuel (DF); electric motor (EM); fuel cells (FC); gigajoules (GJ); internal combustion engine (ICE); kilowatts (kW); mono-fuel (MF); million US dollars (MUSD).

Fuel prices and CO_2 emission factors

We have estimates realistic spans in production and distribution costs per fuel based on a systematic analysis of different fuel-supply chains and the most important cost drivers for carbon-neutral fuels (Brynolf et al., 2018; DNV, 2022; Nelissen et al., 2020).

We only consider tank-to-wake CO_2 emissions in this study. For fossil fuels we use the CO_2 factors in the current EEDI calculation guidelines (MEPC.308(73)), while the other fuels are assumed to have zero tank-to-wake CO_2 emissions. The carbon-neutral variants can be produced in different manners, either from renewable electricity, biomass, or by reforming of natural gas in combination with CCS. The production of these fuels will develop over time, and they may not be fully carbon-neutral from the start. We assume that all bio- variants are made from sustainable biofuels, electro- (e-) variants from renewable electricity, and blue variants from fossil fuels with CCS.

Table A6 shows the CO_2 emission factors and projected fuel prices used in the modelling.

Table A6
Fuels used in the modelling with tank-to-wake CO2 emission factors, and fuel prices to 2050.

Fuel	CO_2 emission factor	Fuel prices (USD/GJ)			
	(tCO_2 per t fuel)	2025	2030	**2040**	**2050**
LSFO+MGO	3.206	10.5	10.4	11.3	11.2
HFO+scrubber	3.114	8.1	8.1	8.7	8.7
LNG	2.75	9.3	9.0	8.6	8.2
LPG	3.00	15.5	15.0	14.1	13.5
e-MGO	0	49.5	46.3	40.3	35.1
e-liquefied methane	0	45.5	43.1	37.5	32.3
e-CH_2	0	54.2	50.8	45.5	39.6
e-methanol	0	42.6	39.9	35.2	31.1
e-LH_2	0	44.0	42.4	36.1	29.4
e-ammonia	0	34.9	33.5	27.1	20.9
blue CH_2	0	43.1	44.3	44.3	43.5
blue LH_2	0	34.9	36.4	34.9	33.8
blue ammonia	0	25.7	27.4	26.2	25.4
bio-MGO	0	26.6	28.0	31.4	35.7
bio-liquefied methane	0	23.9	24.2	25.1	26.8
bio-methanol	0	24.6	25.1	26.9	29.5
electricity from grid	0 (per MWh)	13.4	12.2	12.1	12.3

Key: Biofuel (bio-); fuel produced from fossil energy with CCS (blue); compressed hydrogen (CH_2) synthetic electrofuel (e-); gigajoules (GJ); heavy fuel oil (HFO); liquid hydrogen (LH_2); low sulphur fuel oil (LSFO); liquefied natural gas (LNG); liquefied petroleum gas (LPG); marine gas oil (MGO); megawatt hour (MWh); very low sulphur fuel oil (VLSFO).

References

AFI, 2022. Alternative fuels insight [WWW document]. URL https://afi.dnv.com/ (accessed 1.21.22).

Baresic, D., Rojon, I., Shaw, A., Rehmatulla, N., 2022. Closing the gap: an overview of the policy options to close the competitiveness gap and enable an equitable zero-emission fuel transition in shipping. London.

Bouman, E.A., Lindstad, E., Rialland, A.I., Strømman, A.H., 2017. State-of-the-art technologies, measures, and potential for reducing GHG emissions from shipping – a review. Transp. Res. D Transp. Environ. 52, 408–421.

Brynolf, S., Taljegard, M., Grahn, M., Hansson, J., 2018. Electrofuels for the transport sector: a review of production costs. Renew. Sustain. Energy Rev. 81, 1887–1905.

Dankwa Ampah, J., Yusuf, A.A., Afrane, S., Jin, C., Liu, H., 2021. Reviewing two decades of cleaner alternative marine fuels: towards IMO's decarbonization of the maritime transport sector. J. Clean. Prod. 320, 128871.

de Vries, N., 2019. Safe and Effective Application of Ammonia as a Marine Fuel (thesis). TU Delft.

Dimopoulos, G.G., Georgopoulou, C.A., Stefanatos, I.C., Zymaris, A.S., Kakalis, N.M.P., 2014. A general-purpose process modelling framework for marine energy systems. Energy Convers. Manag. 86, 325–339.

Dimopoulos, G.G., Koukoulopoulos, E.D., Georgopoulou, C.A., 2020. LNG carrier two-stroke propulsion systems: a comparative study of state of the art reliquefaction technologies. Energy 195, 116997.

Dimopoulos, G.G., Stefanatos, I.V., Kakalis, N.M.P., 2016. A process modelling approach to the evaluation of ship machinery configuration alternatives of LNG carriers. Int. J. Thermodyn. 19, 146.

DNV, 2022. Maritime Forecast to 2050 - Energy Transition Outlook 2022.

Eide, M.S., Chryssakis, C., Endresen, Ø., 2013. CO2 abatement potential towards 2050 for shipping, including alternative fuels. Carbon Manag. 4, 275–289.

Eide, M.S., Endresen, Ø., Skjong, R., Longva, T., Alvik, S., 2009. Cost-effectiveness assessment of CO2 reducing measures in shipping. Mar. Policy Manage. 36.

Eide, M.S., Longva, T., Hoffmann, P., Endresen, Ø., Dalsøren, S.B., 2011. Future cost scenarios for reduction of ship CO2 emissions. Mar. Policy Manag. 38, 11–37.

EU, 2023a. Regulation (EU) 2023/1805 of the European parliament and of the council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC.

EU, 2023b. Directive 2003/87/EC of the European parliament and of the council of 13 October 2003 establishing a system for greenhouse gas emission allowance trading within the Union and amending Council Directive 96/61/EC.

Faber, J., Hanayama, S., Zhang, S., Pereda, P., Comer, B., Hauerhof, E., Schim van der Loeff, W., Smith, T., Zhang, Y., Kosaka, H., Adachi, M., Bonello, J.-M., Galbraith, C., Gong, Z., Hirata, K., Hummels, D., Kleijn, A., Lee, D.S., Liu, Y., Lucchesi, A., Mao, X., Muraoka, E., Osipova, L., Qian, H., Rutherford, D., Suárez de la Fuente, S., Yuan, H., Velandia Perico, C., Wu, L., Sun, D., Yoo, D.-H., Xing, H., 2020. Fourth IMO GHG study. Int. Mar. Org. (IMO).

Hellström, M., Rabetino, R., Schwartz, H., Tsvetkova, A., Hammad, S., Haq, U., 2024. GHG emission reduction measures and alternative fuels in different shipping segments and time horizons-A Delphi study. Mar. Policy 160, 105997.

Hu, H., Yuan, J., Nian, V., 2019. Development of a multi-objective decision-making method to evaluate correlated decarbonization measures under uncertainty-The example of international shipping. Transp. Policy (Oxf.) 82, 148–157.

IEA, 2019. The future of hydrogen. Paris.

IEA, 2021. Net zero by 2050 - a roadmap for the global energy sector, 4th revision. Paris.

IHS, 2022. IHS markit database [WWW Document]. URL https://maritime.ihs.com/.

IMO, 2023. 2023 IMO strategy on reduction of GHG emissions from ships. Resolution MEPC.377(80).

Irena, K., Ernst, W., Alexandros, C.G., 2021. The cost-effectiveness of CO2 mitigation measures for the decarbonisation of shipping. The case study of a globally operating ship-management company. J. Clean. Prod. 316, 128094.

Irena, M.I., 2021. Innovation Outlook: renewable Methanol. Abu Dhabi.

ITF/OECD, 2018. Decarbonising Maritime Transport Pathways to Zero-carbon Shipping by 2035. Paris.

Jaramillo Jimenez, V., Kim, H., Munim, Z.H., 2022. A review of ship energy efficiency research and directions towards emission reduction in the maritime industry. J. Clean. Prod. 366, 132888.

Kim, K., Roh, G., Kim, W., Chun, K., 2020. A preliminary study on an alternative ship propulsion system fueled by ammonia: environmental and economic assessments. J. Mar. Sci. Eng. 8, 183.

Lagouvardou, S., Psaraftis, H.N., Zis, T., 2022. Impacts of a bunker levy on decarbonizing shipping: a tanker case study. Transp. Res. D Transp. Environ. 106, 103257.

Lindstad, H., Verbeek, R., Blok, M., Van Zyl, S., Hübscher, A., Kramer, H., Purwanto, J., Ivanova, O., Boonman, H., 2015. GHG emission reduction potential of EU-related maritime transport and on its impacts.

Longva, T., Eide, M.S., Skjong, R., 2010. Determining a required energy efficiency design index level for new ships based on a cost-effectiveness criterion. Mar. Policy Manage. 37, 129–143.

Longva, T., Sekkesæter, Ø., 2021. Assessment of the impact on the fleet of short-term GHG measures, DNV Report no 2021-0262, Rev. 0. Issued in MEPC 76/INF.68/Add.1 to the International Maritime Organisation.

LR, UMAS, 2020. Techno-economic assessment of zero-carbon fuels.

Martin, J., Dimanchev, E., Neumann, A., 2023. Carbon abatement costs for renewable fuels in hard-to-abate transport sectors. Adv. Appl. Energy 12, 100156.

Mjelde, A., Endresen, Ø., Bjørshol, E., Gierløff, C.W., Husby, E., Solheim, J., Mjøs, N., Eide, M.S., 2019. Differentiating on port fees to accelerate the green maritime transition. Mar. Pollut. Bull. 149.

Mjelde, A., Martinsen, K., Eide, M.S., Endresen, Ø., 2014. Environmental accounting for Arctic shipping – A framework building on ship tracking data from satellites. Mar. Pollut. Bull. 87, 22–28.

MMMCZCS, 2021. Industry Transition Strategy. Mærsk Mc-Kinney Møller. Center for Zero Carbon Shipping.

MMMCZCS, 2024. Fuel cost calculator from the Mærsk Mc-Kinney Møller center for zero carbon shipping [WWW document]. URL https://www.zerocarbonshipping.com/cost-calculator/ (accessed 5.1.24).

Mundaca, G., Strand, J., Young, I.R., 2021. Carbon pricing of international transport fuels: impacts on carbon emissions and trade activity. J. Environ. Econ. Manage. 110, 102517.

Nelissen, D., Faber, J., van der Veen, R., van Grinsven, A., Shanthi, H., van den Toorn, E., 2020. Availability and costs of liquefied bio- and synthetic methane – The maritime shipping perspective. CE Delft. Publication code: 20.190236.031.

Nepomuceno de Oliveira, M.A., Szklo, A., Castelo Branco, D.A., 2022. Implementation of maritime transport mitigation measures according to their marginal abatement costs and their mitigation potentials. Energy Policy 160, 112699.

Parry, I., Heine, D., Kizzier, K., Smith, T., 2018. IMF Working Paper.

Psaraftis, H.N., Zis, T., Lagouvardou, S., 2021. A comparative evaluation of market based measures for shipping decarbonization. Mar. Transp. Res. 2, 100019.

Rehmatulla, N., Smith, T., 2015. Barriers to energy efficiency in shipping: a triangulated approach to investigate the principal agent problem. Energy Policy 84, 44–57.

Rehmatulla, N., Smith, T., 2020. The impact of split incentives on energy efficiency technology investments in maritime transport. Energy Policy 147, 111721.
Ricardo, DNV, 2023. Study on the readiness and availability of low- and zero-carbon technology and marine fuels. Submitted as MEPC 80/INF.10 to the international maritime organization.
Romano, A., Yang, Z., 2021. Decarbonisation of shipping: a state of the art survey for 2000-2020. Ocean Coast Manag. 214, 964–5691.
Schwartz, H., Gustafsson, M., Spohr, J., 2020. Emission abatement in shipping – is it possible to reduce carbon dioxide emissions profitably? J. Clean. Prod. 254, 120069.
Smith, T., 2020. The Cost of Reducing Greenhouse Gas Emissions in Shipping, International Transport Forum Discussion Papers No. 2020/18. OECD Publishing, Paris.
Smith, T., Jalkanen, J.P., Anderson, B.A., Corbett, J.J., Faber, J., Hanayama, S., O'Keeffe, E., Parker, S., Johansson, L., Aldous, L., Raucci, C., Traut, M., Ettinger, S., Nelissen, D., Lee, D.S., Ng, S., Agrawal, A., Winebrake, J.J., Hoen, M., Chesworth, S., Pandey, A., 2014. Third IMO GHG study 2014.
Soler, A., Gordillo, V., Lilley, W., Schmidt, P., Weindorf, W., Houghton, T., Dell'Orco, S., 2022. Concawe Report 17/22.
Stefanatos, I.C., Dimopoulos, G.G., Kakalis, N.M.P., 2015. Model-based thermoeconomic assessment and selection of alternative configurations for crude-oil tankers discharge systems. In: ECOS 2015 - 28th International Conference on Efficiency, Cost, Optimization, Simulation and Environmental Impact of Energy Systems.
Stott, P., 2013. A retrospective review of the average period of ship ownership with implications for the potential payback period for retrofitted equipment. In: Proceedings of the Institution of Mechanical Engineers, Part M: Journal of Engineering for the Maritime Environment, 228, pp. 249–261.
Taljegard, M., Brynolf, S., Grahn, M., Andersson, K., Johnson, H., 2014. Cost-effective choices of marine fuels in a carbon-constrained world: results from a global energy model. Environ. Sci. Technol. 48, 12986–12993.
Wang, H., Faber, J., Nelissen, D., Russell, B., St Amand, D., 2010. Reduction of GHG emissions from ships. Marginal abatement costs and cost effectiveness of energy-efficiency measures.