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The cost-effectiveness of CO_2 mitigation measures for the decarbonisation of shipping. The case study of a globally operating ship-management company

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ABSTRACT

The International Maritime Organisation has set a goal to achieve a 50% reduction of the total annual greenhouse gas emissions related to the international shipping by 2050 compared to the 2008 baseline emissions. Thus, companies are looking for solutions and measures to align with the Organisation's goal. Marginal Abatement Cost Curves have been extensively used in the literature to rank several Greenhouse Gas mitigation measures based on their costs of reducing an additional unit of pollution. In this paper an expert-based, bottom-up approach was employed to construct Marginal Abatement Cost Curves for a globally operating ship-management company. Several mitigation measures were examined for the following vessel categories (a) Containerships 8000+ TEU, (b) Containerships 2000–2999 TEU, (c) Bulkers 35000–59999 DWT, and (d) Gas Tankers <49999 CBM. Furthermore, the fuel price fluctuation and carbon taxation were used to investigate the sensitivity of baseline Marginal Abatement Cost Curves. The measures, which remain cost-effective under all sensitivity analyses, undergo a Pareto Analysis and a Marginal Cost-Effectiveness Analysis. The results suggest that most of the recommended mitigation measures are of an operational and technical nature, with exception the burning of Liquified Natural Gas and the installation of Flettner Rotors for the Gas Tankers. The company could save up to 17% CO_2 emissions and approximately 2 million dollars per year compared to the 2019 baseline by employing all recommended mitigation measures to all vessel categories. In addition, Carbon Storage and Capture could become a cost-effective solution with appropriate carbon taxation, but it is not the ultimate solution since it does not lead to independence from fossil fuels. The study also reveals that depending on the operating condition, even within the same vessel category, different mitigation measures should be employed.

1. Introduction

International and coastal shipping is the means of transport for 90% of worldwide trade and emits 2.89% of the global Greenhouse Gas (GHG) emissions (IMO, 2020). Current consumption patterns unfold a potential rapid growth of shipping, faster than other industries, in a business-as-usual scenario, with an undesirable consequence of GHG emissions growth (American Bureau of Shipping, 2019).

In 2018, IMO developed two primary goals to boost the decarbonisation of shipping. Firstly, to achieve 40% and 70% reduction of CO_2 emissions per cargo tonne-mile by 2030 and 2050, respectively. Secondly, to work towards a 50% reduction of the total annual GHG emissions by 2050, in line with the Paris Agreement (ABS, 2019). Both are to be benchmarked against the 2008 related emissions. At the same time, shipping industry is facing European Union's (EU) rising ambitions for Europe's neutrality by 2050 (European Union and European Commission, 2019). The changing socio-technical and political regime indicates the urge for adaptation by the private sector.

Operational and technical solutions and alternative energy sources are extensively examined in literature. Currently, shipping struggles with decarbonisation for a variety of reasons. Inadequate knowledge, lack of resources and internal communication, split incentives between vessels' owners and charterers and immaturity of energy-efficiency related projects are only some of the barriers (Johnson et al., 2014; Rehmatulla and Smith, 2015).

An evolving method to evaluate investments are the Marginal Abatement Cost Curves (MACCs). MACCs explore the Cost-Effectiveness

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Abbreviations

AL	Air Lubrication
BF	Biofuels
CBM	Cubic Meter
CCS	Carbon Capture for Storage and Sequestration
CI	Cold Ironing
CRP	Contra Rotating Propellers
DWT	Deadweight Tonnage
FC	Frequency Converters
FR	Flettner Rotors
GHG	Greenhouse Gases
HFC	Hydrogen Fuel Cells
HFO	Heavy Fuel Oil
IMO	International Maritime Organisation
IPRU	Integrated Propeller and Rudder Upgrade
IRR	Internal Rate of Return
LNG	Liquified Natural Gas
LSFO	Low-Sulphur Fuel oil
MACC	Marginal Abatement Cost Curves
MCE	Marginal Cost-Effectiveness
MDO	Marine Diesel Oil
MEAT	Main Engine Auto-Tuning
MM	Mitigation Measures
NPV	Net Present Value
OTB	Optimization of Trim and Ballast
OWFO	Optimized Water Flow of Hull Openings
PBCF	Propeller Boss Cap with Fins
PM	Propeller Maintenance
SP	Solar Panels
TEU	Twenty-Foot Equivalent Unit
VE	Voyage Execution
WACC	Weighted Average Cost of Capital
WED	Wake Equalizing Duct
WHR	Waste Heat Recovery

(CE) which indicates the costs for achieving a specific goal. In terms of clean technologies, this is the cost of reducing one unit of pollution (Sotiriou et al., 2019). It incorporates the future value of money and the lifetime of the investment. It is perceived as more suitable for setting up a decarbonisation plan (Sotiriou et al., 2019). The expert-based, bottom-up approach of MACCs ranks the Mitigation Measures (MMs) from the lowest to the highest marginal abatement costs and specifies the associated emissions reduction (Sotiriou et al., 2019). Technical detail of each measure is well-captured, and this approach is perceived as the most suitable for the private sector (Huang et al., 2016).

Expert-based MACCs can be found in an excellent volume of articles dealing with the CE of MMs for the shipping industry. Most of the articles are exploring the MMs from the social planner perspective. Some articles are implicitly dealing with the private perspective using public databases from previous studies or online sources. These studies aimed at optimizing MACCs to support a well-founded decision-making analysis by the private sector. Hoffmann et al. (2012) highlighted the need for company-specific financial analysis as the use of actual data gathered by an established firm can produce more reliable and robust results.

Additionally, many authors focused on overcoming the shortcomings of MACCs and improving the method's robustness. An overview is provided in section 2. Each study explores a specific shortcoming.

To address some of the shortcomings of MACCs, Pareto Principles and Marginal Cost-effectiveness (MCE) were used. Pareto Principles aim at prioritising the measures based on the comparison of net cost savings and the emissions savings (Ibn-Mohammed, 2017, p.68). MCE is the additional cost per the additional reduction of emissions, and it supports the prioritisation of measures by comparing the additional costs with a predefined threshold (Yuan and Ng, 2017). Thus, this paper combines previously explored solutions to provide an integrated approach.

Currently, there is no research performed with actual data from a specific company to prioritise the MMs. This study uses as a case study, a multinational ship-management company. The company aims at exploring CE of MMs for ten vessels owned and managed by them, and thus data regarding the operational and technical profile of vessels were readily available by the company. Hence, the following research question is formulated: "*Which MMs are the most cost-effective and should be prioritised for reducing the CO_2 emissions from vessels based on the case study of a globally operating ship-management company?*".

The aim of our research work was to investigate several GHG MMs for different types of vessels and rank them based on their cost-effectiveness. This would allow the comparison between MMs for one vessel type as well as the comparison between the performance of different vessel types. At the same time, the purpose of our work was to enhance the MACCs methodology accuracy by using company-specific data and by integrating the Pareto Principles and MCE in exploring the most suitable solutions for each vessel type. The theory behind MACCs is elaborated in Section 2, while the methods used, and the assumptions made are described in Section 3. Sections 4 and 5 present and discuss the results and the conclusions are drawn in Section 6.

2. Theory

2.1. Introducing MACCs

MACCs are extensively used for supporting decision-making for the employment of GHG MMs. They serve as a way of dealing with the trade-offs and conflicts between environmental protection and economic development. The MACCs literature presents a variety of calculations used for solving different types of problems leading to diversified results and interpretations. Huang et al. (2016) provide an overall classification of the MACCs based on their evaluation method and information type. This study focuses on the expert-based bottom-up approach that elaborates on the technical detail and the associated costs of each measure (Jiang et al., 2020). It is suggested to be the most appropriate for the private sector. Most studies use this method since it is less complicated and facilitates the communication of the results (Jiang et al., 2020).

In this Section, we first present how MACCs are used for the shipping industry, that relates to our first research aim, and then an overview of the MACCs shortcomings is provided, indicating the necessity of combining MACCs with other methodologies to obtain the best results.

2.2. MACCs used for the shipping industry

MACCs were used to identify the most cost-effective decarbonisation pathway for shipping. The boundaries of the several studies differ in terms of the baseline scenarios, the number of abatement measures into consideration and their interactions, the fleet segment (type, size, age, current technologies), and lastly, the discount rate used (social or a private perspective). The assumptions concerning the fleet growth rate, the future fuel price, the future uptake of technologies, and the economic incentives given, such as carbon taxes and carbon prices vary among studies (Bouman et al., 2017; Hu et al., 2019).

One of the main barriers to energy-efficiency in shipping is the split incentives of the charter agreements (Faber et al., 2012; Rehmatulla and Smith, 2015). The charter agreements display differences in the allocation of costs, benefits, responsibilities, liabilities, and risks (Plomaritou, 2014). Split incentives for energy-efficient technologies are evident in time charters as the shipowner bears the costs of the investment while the one who benefits from the reduction of energy bills is the charterer (Faber et al., 2011).

Faber et al. (2012) refers to the information asymmetry regarding the energy-efficiency of vessels. If monitoring systems are not installed, the crew is responsible for reporting the fuel consumption with potential false disclosures. Additionally, the authors highlight the shipowners' concerns for the information given by manufacturers or academia regarding energy-efficiency and innovation, the high upfront investments of many energy-efficient technologies, and the reluctance of banks to loan money for immature technologies enhancing their financial burden.

2.3. MACCs shortcomings & optimization

MACCs suffer from several shortcomings that reduce the reliability and robustness of the results. The discount rate used could have a social or private perspective. The former designates the beneficial policies or investments for society. In contrast, the latter reflects the private costs of capital, the several private risks (e.g., price volatility or regulatory risks), and therefore indicates the market's direction. A MACC is a snapshot of time, and therefore several temporal uncertainties and the path dependency can significantly affect the outcome. Uncertainties are produced from both the input data as well as the assumptions made. Thus, there is a need for transparency and openness regarding the data sources used and the methodology followed to avoid misleading decision-making.

Furthermore, some MMs might be correlated (Kesicki and Ekins, 2012), meaning that they can reduce emissions in the same way or cannot be applied simultaneously due to physical constraints. Bypassing such limitations might lead to double counting of the abatement potential (Kesicki and Ekins, 2012). Additionally, the measures are ranked from the lowest to the highest marginal abatement costs. When comparing measures with positive values of marginal abatement costs, the most cost-effective option could be the outcome of lower net costs and higher or equal emissions savings. However, in the case of negative values of marginal abatement costs, the most cost-effective option could result from lower net costs and lower or equal emission savings (Huang et al., 2016). The lower emission savings is an unfavourable condition. Therefore, the ranking of MMs with negative marginal costs is one of the main shortcomings of MACCs.

Several studies focused on the elimination of the shortcomings, the improvement, and the innovation of MACCs. Pareto Principles were used to support the decision-making for MMs with negative marginal abatement costs (Taylor, 2012). According to Taylor (2012), Pareto Optimality[1] can be achieved when the net costs are better off while emissions abatement is not worse off. Therefore, the MM which performs better in terms of both cost savings and emissions savings, is preferred. Levihn (2016) suggested that Pareto Optimality as a solution is not appropriate. Two different options can have equal efficiency (meaning that they are both at the Pareto Frontier), resulting from a distinct correlation between marginal costs and marginal abatement values. Yuan and Ng (2017) proposed the use of MCE as the criterion to rank the MMs, which are in the Pareto Frontier. MCE is the additional cost per the additional reduction of emissions Yuan and Ng (2017). By comparing the MCE with a specific threshold (accepted expenses for a metric tonne of emissions abated) as determined by the policymaker, one can decide which measure will be prioritised Yuan and Ng (2017).

The uncertainty of input data was addressed by Kesicki and Ekins (2012), who proposed the use of sensitivity analysis where one input varies while the others are kept stable. Eide et al. (2013) used scenario analysis of "pessimistic" and "optimistic" cases. Other authors highlighted the need to use stochastic and probabilistic models instead of deterministic ones (Yuan et al., 2016; Hu et al., 2019). For a more comprehensive decision-making, a multi-criteria analysis was used with the MACCs analysis as one of the criteria (Odijk, 2012; Melo et al., 2013).

[1] Pareto Optimality is the state at which a further reallocation of goods will benefit one person while harming another (Chappelow, 2019).

3. Methodology

3.1. Research Design

It is important to define the boundaries of the research including the number, type of vessels and their current performance. Moreover, as a large volume of MMs exists, it is crucial to explore their technical feasibility for the specific vessels. The data was collected from a variety of sources. For example, data regarding the performance of vessels were provided from the company whereas data regarding the characteristic of measures was collected through a desk-research or consultation with industry experts. After collecting the data and exploring the applicability of MMs on each vessel category, the CE of the applicable MMs was calculated. A sensitivity analysis was also performed since several parameters are based on assumptions. Lastly, Pareto and MCE analyses were used to further rank the cost-effective MMs, and recommendations were made (cf. Fig. 1).

3.2. Case study

This study deals with the MACCs in a private sector's perspective aiming at facilitating the decision-making of an established ship-management firm regarding the implementation of MMs. To collect the most reliable data and achieve an in-depth analysis ten vessels are taken into consideration. These vessels are both owned and managed by the company, and they are representative of the company's main category assets. The future fleet development was not considered within the boundaries of this research since it is a highly unpredictable parameter. Table 1 presents the type, size, and age of the vessels. With a maximum lifetime of 25 years, all examined vessels will be part of the fleet in 2030.

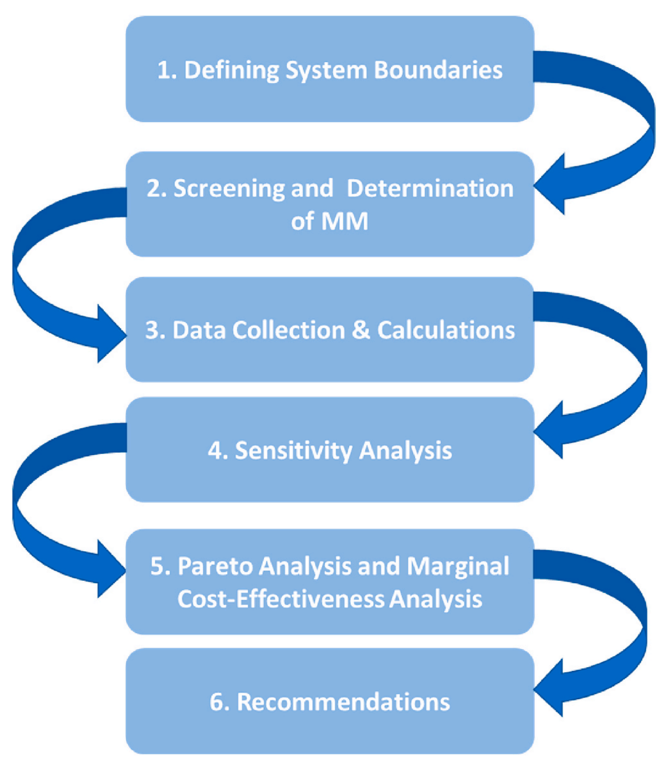

Fig. 1. Research design.

Table 1
Categorization of the examined fleet.

Vessel Type	Size Type	Age	Age Group Category
Containership	8000+ TEU	7	5–10 years old
		7	
		7	
Containership	2000-2999 TEU	5	0–5 years old
		3	
		3	
Bulk Carriers	35000-59999 DWT	1	0–5 years old
		1	
Gas Tankers	<49999 CBM	5	0–5 years old
		3	

3.3. Calculation of CE

The abatement costs of each MM consist of the initial investment, the annual maintenance, and operational costs, the opportunity costs due to the loss of service and the reduced costs of fuel consumption. The investment costs are discounted to today's value by using the sector's Weighted Average Cost of Capital (WACC) as the discount rate.

The annuitized investment costs depend on the lifetime of each measure or the remaining lifetime of the vessel, whichever is smaller. The opportunity costs relate to the dry-docking days for retrofit. This study assumes that MMs will be applied during the next scheduled dry dock. Therefore, there were no opportunity costs. The economic benefit of the investment arises in the form of fuel savings or CO_2 emissions savings in the case of carbon taxation. The abatement potential is expressed as a percentage of fuel reduction. CO_2 emissions are proportional to fuel consumption, and therefore the same abatement potential is used (Andreoni et al., 2008). The CE is calculated considering the individual MMs as "stand-alone" option. Equation (1) illustrates the CE calculation:

$$\boldsymbol{CE} = \frac{\left[\boldsymbol{IC}^{*}\left[\boldsymbol{WACC}/\left(1-(1+\boldsymbol{WACC})^{-\boldsymbol{L}}\right]+\boldsymbol{OP}+\boldsymbol{OC}-\left(\boldsymbol{FC}^{*}\boldsymbol{FP}^{*}\boldsymbol{AP}\right)\right.\right.}{\boldsymbol{E}^{*}\boldsymbol{AP}} \tag{1}$$

CE = CE ($2020/tn$CO_2$).
IC = Investment Costs ($2020).
WACC = Weighted Average Cost of Capital (%)
L = Lifetime of the measure or the remaining lifetime of the vessel after the next dry dock, whichever is shorter (years).
OP = Operational Costs ($2020/year).
OC = Opportunity Costs ($2020/year).
FC = Fuel Consumption of the vessel in the reference year (MT).
FP = Fuel Price ($/MT).
E = CO_2 Emissions in the reference year (MT).
AP = Reduction of Fuel Consumption Potential from the relevant engine (%)

The MACCs have 2030 as a target year, and the average values of CE (y-axis) and annual CO_2 emissions reduction (x-axis) for each MM of vessels within the same category are used to illustrate the MACCs. Thus, MACCs are representative of the average performance of a specific vessel category. Desk research and consultation with several industry experts allowed a screening process of the MMs. There is a risk of safety hazards and physical constrains when implementing several MMs at the same time. Some MMs reduce the energy use of a vessel similarly, and their combination does not provide any additional reduction. Hence, their combination lead to double counting of the abatement potential. These MMs are marked as highly correlated. Table 2 provides the most appropriate combination of MMs on a vessel, and MMs within the same group cannot be simultaneously applied.

The CE calculation for CCS and Alternative Energy Sources differs compared to other energy-efficiency measures. CCS is an end-of-pipe solution which captures the CO_2 emissions. Therefore, it does not reduce the fuel consumption. It is assumed that the system will be able to capture all CO_2 emissions produced by the main engine. Alternative Energy Sources allow for energy production with lower CO_2 emissions. SP, Kites and FR are applied only to Bulker and Gas Tankers as they require sufficient deck space.

Table 2
MMs grouping.

Category	MM Group				
Operational Measures	Voyage Execution (VE)				
	Optimization of Trim & Ballast (OTB)				
	Propeller Maintenance (PM)				
Technical Measures	Optimized Water Flow of Hull Openings (OWF)				
	Air Lubrication (AL)				
	Propeller Efficiency Devices:	*Integrated Propeller and Rudder Upgrade (IPRU)*	*Propeller Boss Cap with Fins (PBCF)*	*Contra Rotating Propeller (CRP)*	*Wake Equalizing Duct (WED)*
	Frequency Converters (FR)				
	Waste Heat Recovery (WHR)				
	Main Engine Auto – Tuning (MEAT)				
	Carbon Capture and Storage (CCS)				
Alternative Energy Sources	Cold Ironing (CI)				
	Solar Panels (SP)				
	Wind Energy:	*Kites*	*Flettner Rotors (FR)*		
	Main Engine Fuels:	*Liquified Natural Gas (LNG)*	*Biofuels (BF)*		
	Hydrogen Fuel Cells (HFC)				

For CI, it is assumed that the annual kWh produced by the auxiliary engine while the vessel is at berth will be provided by shore power. Moreover, it is assumed that the vessel uses Marine Diesel Oil (MDO) and Low Sulphur Fuel Oil (LSFO) as the primary sources of energy when at berth as many ports do not allow the use of Heavy Fuel Oil (HFO). In case of additional energy needs, when the total amount of MDO and LSFO is used, the vessel uses HFO. The average worldwide electricity price of 0.13 $/kWh is used to calculate the fuel costs for replacing fossil fuels with shore power (Electricity Prices, 2019). The CO_2 abatement potential is calculated using the following emission factors: HFO – 722 grCO_2/kWh, LSFO – 722 grCO_2/kWh, MDO – 620 grCO_2/kWh (Merk, 2014).

For other alternative fuels, the energy contents of the currently used fuels are used to calculate the amount of alternative fuels needed to meet the vessel's energy demands (cf. Appendix B). LNG replaces the fuel used by the main engine, hydrogen replaces the fuel used by the auxiliary engines as auxiliary engines are replaced by fuel cells, and finally BF replace the fuels used in both the main and the auxiliary engine with no costs involved for engines' modification.

3.4. Data collection

This study uses 2019 as reference year and a frozen efficiency scenario, meaning that it is assumed that in 2030 the vessels will operate under the same conditions as in 2019. The average baseline emissions for each vessel category and the overall fleet's average are used. Table 3 provides an overview of the company-specific data and the data gathered by desk-research and consultation with industry's experts. Comprehensive information for each MM is shown in Appendix A.

The abatement potential is either related to the fuel consumption's reduction of main or auxiliary engine or related to the reduction of the vessel's total CO_2 emissions. Therefore, the following auxiliary to main engine power ratios were used to calculate the amount of fuel consumed to each engine; 0.220 for Containership, 0.211 for Gas Tankers, and 0.222 for Bulk Carriers (Browning, 2006). Lastly, the discount rate is based on the transportation and logistics sector's WACC, which is found to be 6% (WACC and over the last 12 months, 2020).

Fuel prices are very volatile and highly unpredictable parameters

Table 3
Data collection process.

Company-Specific/Actual Data	Online Sources	Industry Experts
Types and Quantities of Fuels (MT)	MMs' Applicability	Investment, Operational Costs and Abatement Potential for WED – LOEWE Marine Company
Total CO_2 Emissions (MT)	MMs' Abatement Potentials	
Days at Sea and Days at Berth	MMs' Investment/Operational Costs	
Main and Auxiliary Engines Types	MMs' Lifetime	Investment, Operational Costs and Abatement Potential for Kites –Skysails Company
Main and Auxiliary Engines Performance (KW)	Fuel Prices	
Age of Vessels	Fuels' Energy Content	Investment, Operational Costs and Abatement Potential for FR – Norse Power Company
Last Dry Dock	Emission Factors	
	WACC	Investment, Operational Costs and Abatement Potential for CCS – DecarbonICE project

Table 4
Potential implementation of additional non-cost-effective MMs.

Vessel Category	Cost Savings (k$2020)	Additional MM	Emission Reduction Potential (%)
Containerships 8000+ TEU	1131	CCS	104%
Containerships 2000–2999 TEU	622	CCS	118%
Bulkers 35000–59000 DWT	63	none	/
Tankers <49999 CBM	861	CCS, AL[a]	134%
Average Fleet	2678		104%

[a] CRP is avoided since PBCF is already assumed to be installed. BF is not considered since LNG is assumed to be used.

(Lindstad et al., 2015). To capture the variation of prices, the global average price of twenty ports from October 2019 till July 2020 is used for each fuel type (Ship and Bunker, 2020a,b). Specifically, the fuel types are HFO – 300 $/MT, LSFO – 450 $/MT, and MDO – 350 $/MT. Appendix B provides an overview of the data used for all fuel types.

3.5. Sensitivity analyses

To assess the sensitivity of the results, several influential parameters were changed systematically one at a time. This study focused on two parameters: fuel prices and carbon tax. The aim was to capture the way the results differentiate when the input data changes or to additional parameters that reflect the overall industry's future.

This research baseline scenario used 2020s fuel prices. These were highly influenced by two significant events which took place in 2020; the introduction of the legislation to limit the sulphur emissions in shipping and the COVID-19 crisis. The former caused an increase in the demand of LSFO and decrease in the demand of HFO (Kulsen and Loozen, 2020). The latter caused a decrease in demand for HFO due to the lockdowns (Global bunker fuel demand set to drop 5% - 10% on COVID - 19 - pain - expert, 2020). It is evident that the fuel prices used in the baseline scenario are inherently affected by the pandemic crisis. This study explores the effect of the fossil fuel prices on the results under two potential cases: doubling or halving of the 2020's prices.

To regulate the emissions of the shipping sector, many countries implement or schedule to implement a carbon tax scheme (BHP Group Limited et al., 2019). A carbon tax of the order of 30 $/$CO_2$MT is applied (BHP Group Limited et al., 2019). Specifically, the annual abated emissions are multiply by the carbon tax. The value indicates the annual cost savings by avoiding carbon taxation.

3.6. Pareto and MCE analyses

Pareto and MCE analyses prevent the prioritisation of a MM, with better CE due to lower emissions savings. This is a major shortcoming when prioritising MMs with negative marginal costs. The Pareto analysis allows the comparison of MMs in terms of their performance in two objectives: net cost savings ($2020) and emissions savings (MT CO_2). The most desirable MM is the one that achieves simultaneously high costs savings and high emissions savings. For example, measure "i" dominates (and therefore ranks higher) measure "j" when it has a higher or equal value of cost savings and higher value of emissions savings. Measure "i" also dominates measure "j" when it has higher cost savings and higher or equal value of emissions savings. In case that only one out of the two parameters is met, the MMs are considered as equal.

For equally ranked MMs, a final analysis using MCE, as proposed by Yuan and Ng (2017), allows the completion of the ranking. MCE indicates the additional costs for an additional MT of emissions abated by the implementation of one measure over the other. If measure "i" has lower cost savings than measure "j" and, at the same time, measure "i" achieves higher emissions savings than measure "j", then Equation (2) is used to calculate the MCE of the two MMs.

$$\text{MCEij} = \frac{CS\ (i) - CS(j)}{ES\ (i) - ES\ (j)} \tag{2}$$

MCE = Marginal CE ($2020/MT CO_2).
CS = Costs Savings ($2020).
ES = Emissions Savings (MT CO_2).

When the MCE is below the threshold of 30 $/MT which equals to a possible carbon tax, measure "i" dominates measure "j". The MM with the biggest number of dominations over other MMs ranks first.

In this study, the Pareto and MCE analyses were used for two reasons. Firstly, to describe the results of the baseline MACCs and sensitivity analysis results as only one of the correlated MMs should be selected to avoid double counting of total emission savings. Hence, Pareto and MCE analyses were used for an appropriate selection. Secondly, MMs which preserved their cost-effectiveness under all sensitivity analyses underwent Pareto and MCE analyses resulting in the final ranking.

4. Results

In this section, we present the baseline MACC of the following vessel categories: Containerships 8000+ TEU, Containerships 2000–2999 TEU, Bulkers 35000–59999 DWT, and Gas Tankers <49999 CBM. Additionally, the sensitivity analyses MACCs for Containerships 8000+ TEU are illustrated coupled with the details of Pareto and MCE analyses. The sensitivity analyses MACCs for the other vessel categories are presented in Appendices C, D and E. Similarly, the results of Pareto and MCE analyses are presented in Appendix F.

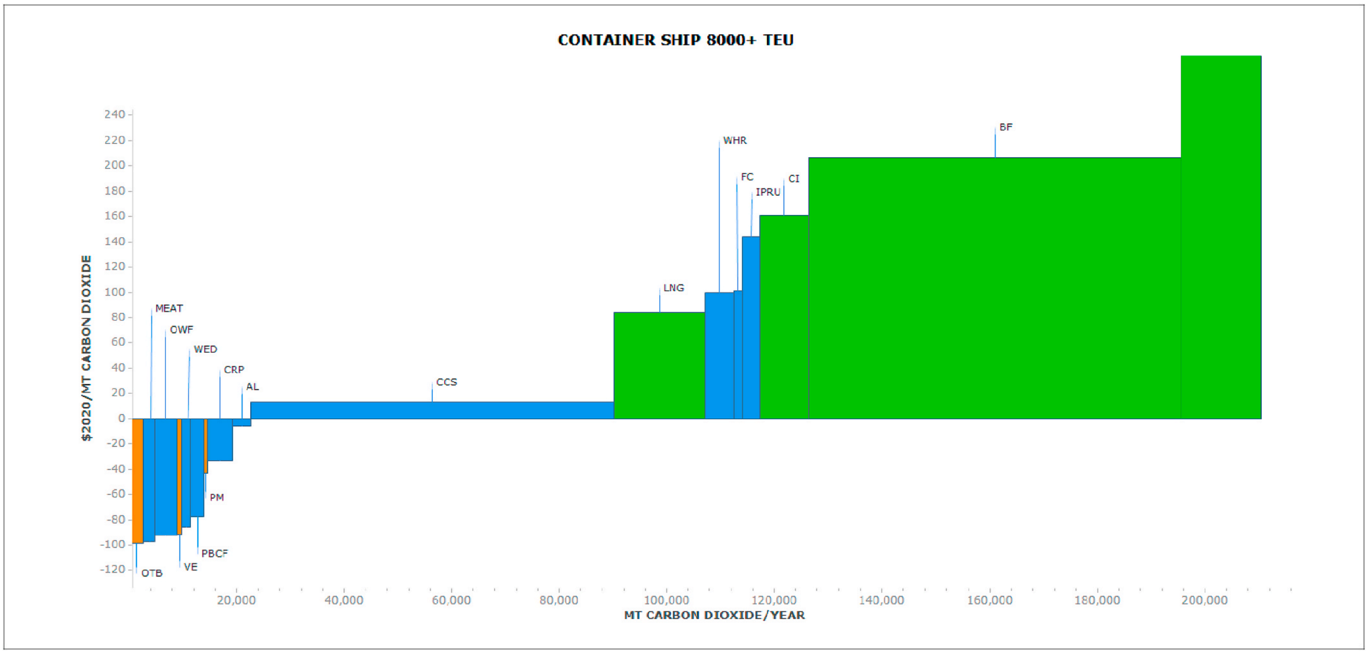

Fig. 2. Baseline MACC of containership 8000+ TEU. Orange: Operational measures, green: Alternative energy sources, blue: Technical measures. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

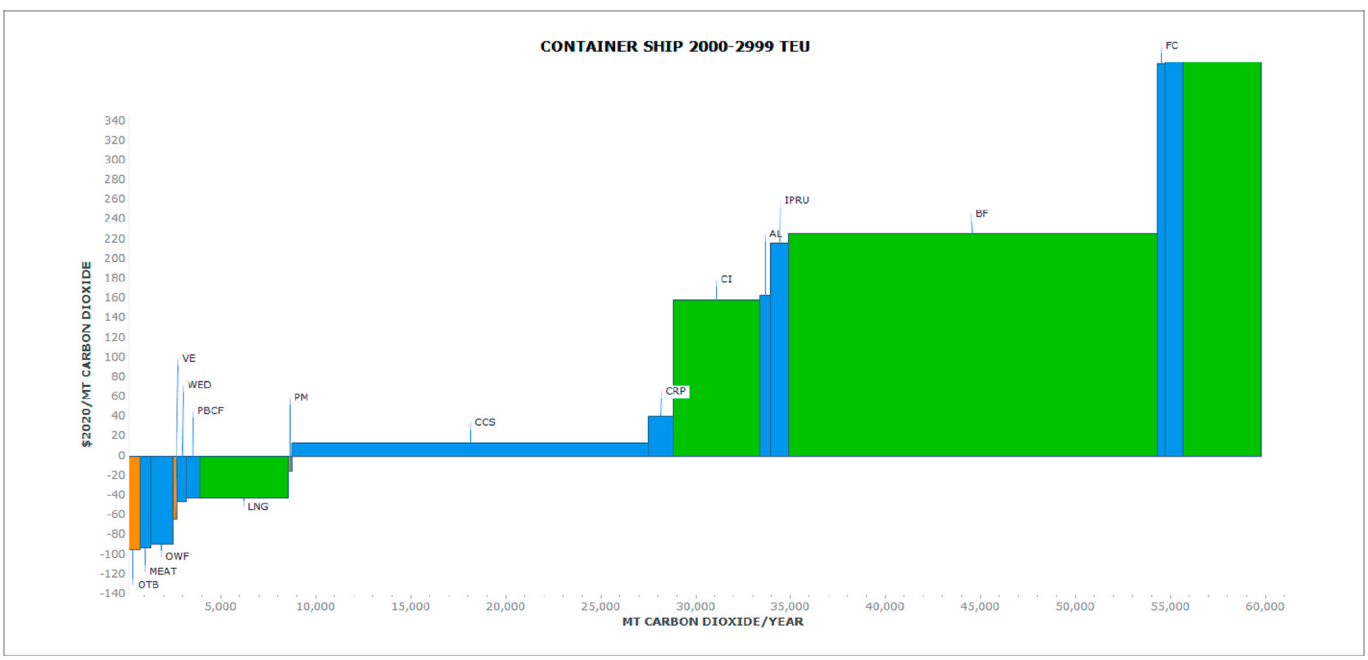

Fig. 3. Baseline MACC of containerships 2000–2999 TEU. Orange: Operational measures, green: Alternative energy sources, blue: Technical measures. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

4.1. Baseline MACCs

Figs. 2–5 illustrate the aggregated MACCs for Containerships 8000+ TEU, Containerships 2000–2999 TEU, Bulkers 35000–59999 DWT, and Gas Tankers <49999 CBM, respectively.

Results show that 55% of the tested MMs on Gas Tankers have negative marginal abatement costs, followed by 53% on Containership 8000+ TEU, 47% on Containerships 2000–2999 TEU, and lastly 35% on Bulkers. It should be noted that in the case of Containerships 8000+ TEU, PBCF, CRP, and WED are highly correlated and cannot be installed together on the same vessel. For Containerships 2000–2999 TEU and Bulkers, PBCF is highly correlated with WED. Similarly, in the case of Gas Tankers, IPRU, PBCF, and WED, as well as Kites and FR, are highly correlated MMs.

All MMs were illustrated in the MACCs, and their ranking is based on the MMs' CE. However, only one of the highly correlated MMs should be considered to avoid double counting. Thus, a Pareto analysis (and in the case of equally ranked MMs, an MCE analysis) was applied to decide upon one of the correlated MMs. Hence, CRP is preferred over PBCF and WED for Containerships 8000+ TEU. PBCF is preferred over WED for Containerships 2000–2999 TEU, and WED is preferred over PBCF for Bulkers. Finally, PBCF is preferred over IPRU and WED, and Kites are

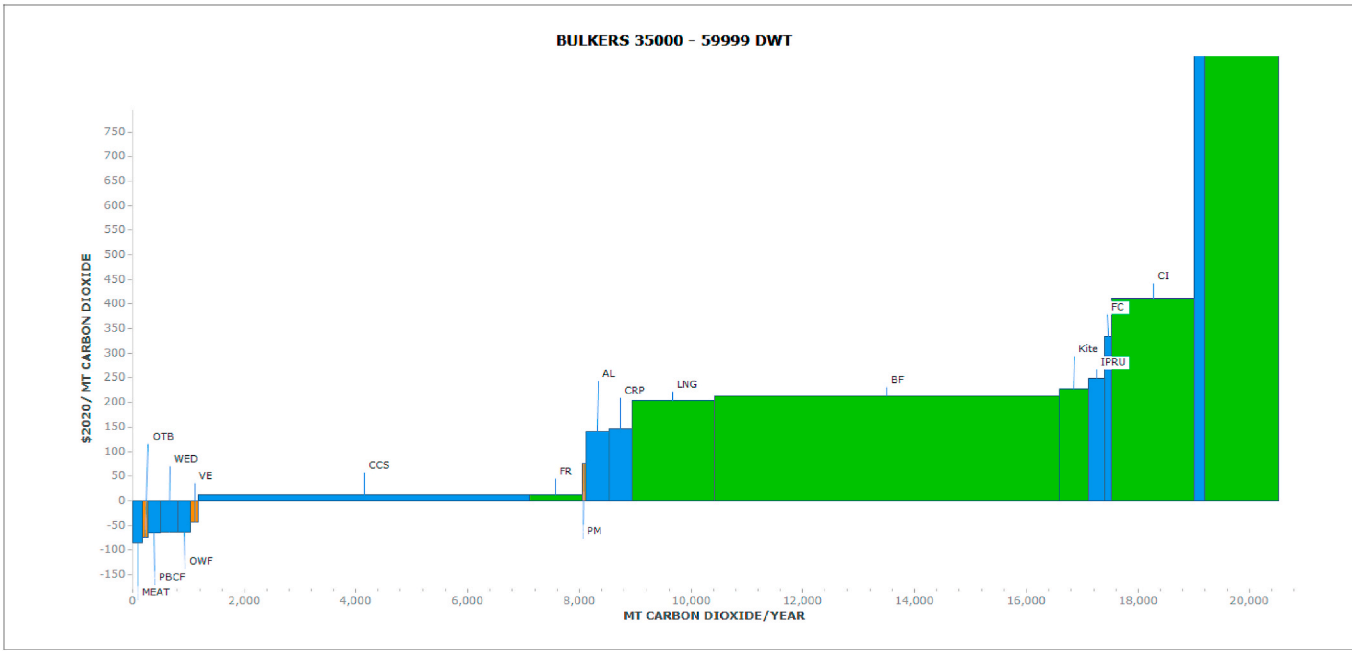

Fig. 4. Baseline MACC of bulkers 35000–59999 DWT. Orange: Operational measures, green: Alternative energy sources, blue: Technical measures. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

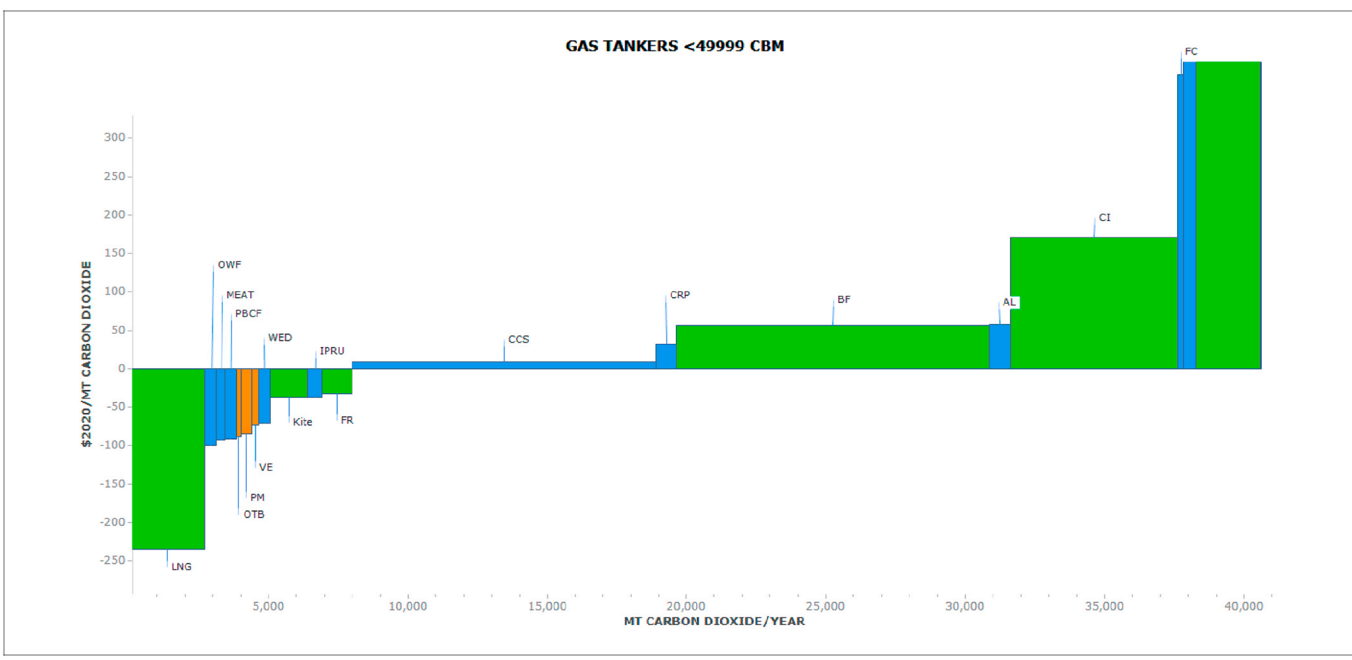

Fig. 5. Baseline MACC of gas tankers <49999 CBM. Orange: Operational measures, green: Alternative energy sources, blue: Technical measures. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

preferred over FR for Gas Tankers.

Based on the decision drawn above Containerships 8000+ TEU can achieve 22.4% emission reduction cost-effectively compared to the baseline emissions. Similarly, Containerships 2000–2999 TEU can achieve a 36.3% reduction, Bulkers 13%, and Gas Tankers 45.5%. If all cost-effective MMs are applied to all vessels, the examined fleet can achieve an overall average emission reduction of 27% cost-effectively in 2030 (cf. Table 5).

Operational MMs are amongst the most cost-effective options for all four vessel categories. HFC presents poor CE due to the very high investment costs of HFCs and the high hydrogen prices. SP is the least cost-effective option for Tankers and Bulkers. Even though HFC has higher costs compared to SPs, it also achieves higher emissions savings. Both HFC and SP reduce the fuel consumed by the auxiliary engine, which consumes less compared to the main engine causing the measures' malperformance.

In many cases, CCS performs better compared to other longer established MMs such as WHR and FR. However, as aforementioned, CCS input data is very optimistic based on the expectations of the DecarbonICE, 2020 Team project. Therefore, future re-calculation with actual input data deriving from CCS sea trials is desirable.

Remarkably, LNG acquires negative marginal abatement costs in the case of Containership 2000–2999 TEU and Gas Tankers. The LNG

Table 5
The emission reduction potential of cost-effective MMs compared to the Vessel's Category average emissions under each scenario.

Vessel Category	Baseline	Carbon Tax	Fuel Price Doubling	Fuel Price Halving
Containerships 8000+ TEU	22.4%	100%	39.2%	14%
Containerships 2000–2999 TEU	36.3%	97.8%	39%	12%
Bulkers 35000–59999 DWT	13%	95%	13%	11%
Gas Tankers <49999 CBM	45.5%	128%	52%	40.5%

readiness of Gas Tankers justifies the latter. One out of the three vessels examined for the Containership 2000–2999 TEU category, due to its long time at sea compared to the other two, consumed larger amount of fuel, causing an overall negative average marginal abatement costs for LNG as it is cheaper than the other fossil fuels. The other two vessels exhibited slightly positive marginal abatement costs for LNG. This difference indicates that LNG could become a viable solution based on the operation level of vessels within this category.

If a company would like to achieve a higher reduction of their vessels' emissions additional MMs with positive marginal costs should be employed. The cost savings from the implementation of cost-effective MMs could be allocated to other MMs which do not provide a return on investment. The implementation of all MMs with negative marginal costs on Containerships 8000+ TEU could save a net of 1131 k$2020 per year. CCS, the next most cost-effective option, has an average total annual expense of 902 k$2020 and could save up to 67,5 MT CO_2. Its implementation could lead to zero-emission vessels. Table 4 provides the average cost savings of each category when all cost-effective MMs are implemented. It also indicates which non cost-effective MMs could be employed if the cost savings cover the additional costs. Lastly, it shows the emission reduction achieved.

One should be very cautious when interpreting the results of Table 4. It suggests that carbon-free shipping could be achieved. However, this relies to a great extent on the successful use of CCS technology. CCS may be an ideal mid-term solution for shipping decarbonisation, but it does not allow for fossil fuels' independence. In other words, even though the technology could significantly reduce emissions, the efforts for developing more energy-efficient vessels that are able to use cleaner fuels should be the way forward in the long term.

4.2. Sensitivity analyses

The sensitivity analyses of Containership 8000+ TEU is presented in this section. As abovementioned, sensitivity analyses MACCs for the other vessel categories can be found in Appendices C, D and E. For all vessel categories, the same rationale was followed as the one described in this section for Containership 8000+ TEU. The aim was to explore which MMs maintain their cost-effectiveness when they undergo sensitivity analyses.

Figs. 6–8 represent the Containerships 8000+ TEU MACCs for fuel price doubling, fuel price halving, and carbon taxation, respectively.

The doubling of fuel prices results in an overall 39.2% emissions savings in 2030 at marginal <0 \$/MT CO_2 compared to the baseline MACC. Dissimilarly, the halving of fuel prices decreases the total emission reduction potential, at negative marginal costs, to 14% in 2030 compared to the baseline.

Doubling of fuel prices results in LNG obtaining negative marginal abatement costs, whereas all previously negative marginal abatement costs options ameliorate. Notably, CRP and AL become less cost-effective compared to LNG. LNG has high investment costs while it has a lower price (150 $2020/MT) than the prices of conventional fuels, namely HFO, LSFO, and MDO. Doubling of the conventional fuel prices implies higher cost savings, which in the case of LNG, can counterbalance the investment costs. In contrast, the halving of fuel prices results in PM, AL, and CRP positive marginal abatement costs. The fuel cost savings become lower than the expenses to install these MMs, leading to their unprofitability. The order of the other MMs with negative marginal abatement costs remains the same but they all become less cost-effective compared to the baseline MACC.

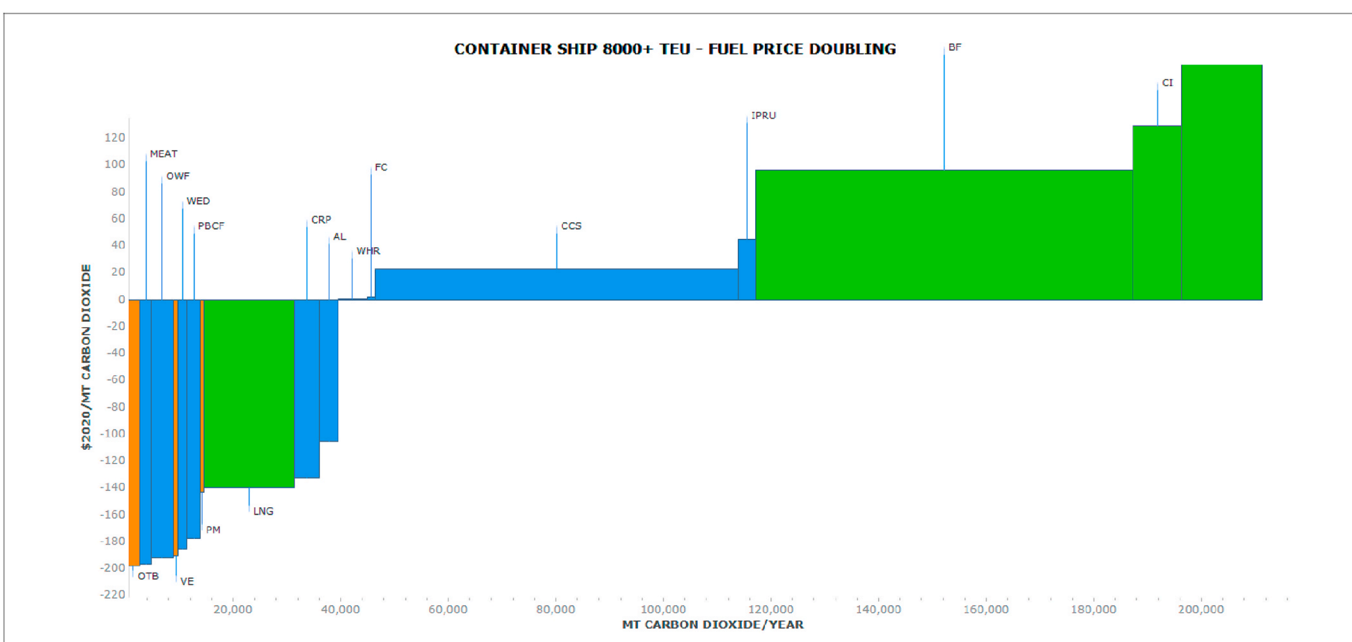

Fig. 6. MACC of containership 8000+ TEU – double fuel prices. Orange: Operational measures, green: Alternative energy sources, blue: Technical measures. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

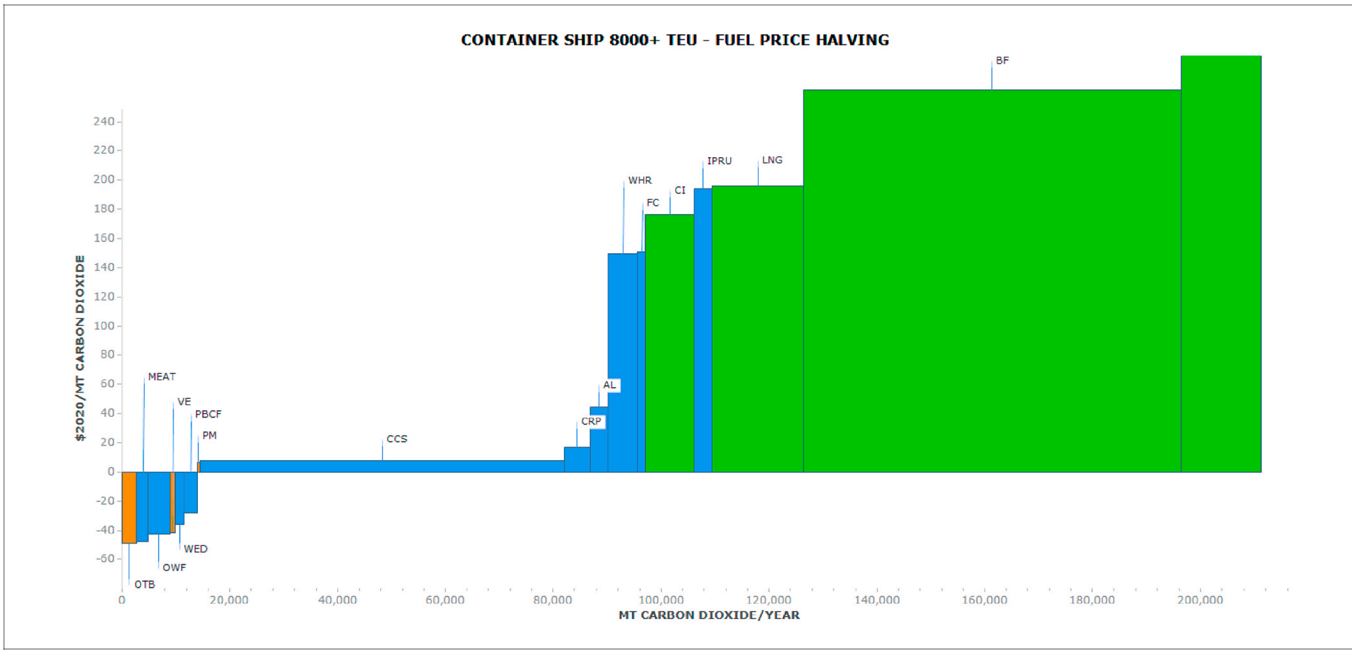

Fig. 7. MACC of containership 8000+ TEU – half fuel prices. Orange: Operational measures, green: Alternative energy sources, blue: Technical measures. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

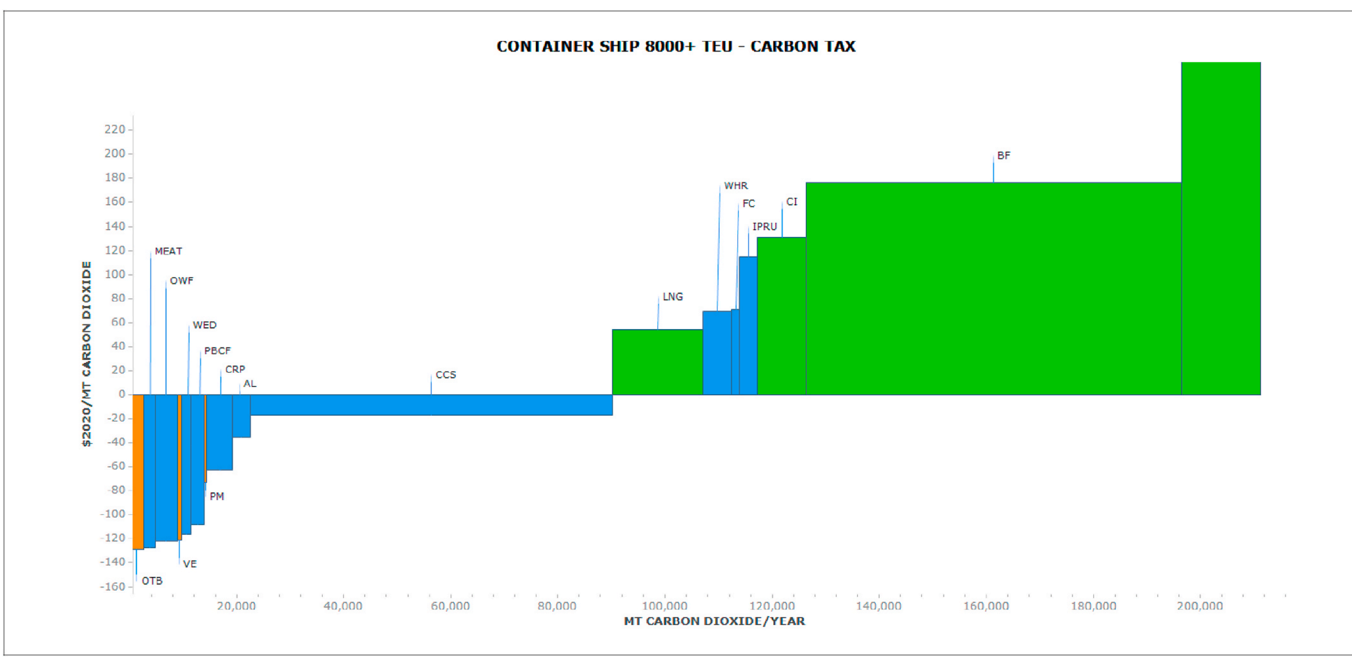

Fig. 8. MACC of containership 8000+ TEU – carbon tax. Orange: Operational measures, green: Alternative energy sources, blue: Technical measures. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

As illustrated in Fig. 8, the carbon tax enforcement improves the CE of all MMs. The order of MMs with negative marginal costs is the same as the baseline MACC. CCS achieves negative marginal abatement costs. CCS can significantly reduce the emissions (100% abatement potential for the main engine-related emissions), and therefore, a carbon tax avoidance implies substantial monetary savings. That is not the case for LNG, which in other sensitivity analyses achieved negative marginal abatement costs. Even though carbon taxation improves its CE, it does not attain negative values as LNG can reduce the emissions only by 25%. If the full potential is realized, the carbon tax could result in a 100%

Table 6
Sorting of cost-effective MMs based on Sensitivity Analyses.

Vessel Category	Sorting of MM
Containerships 8000+ TEU	OTB, MEAT, OWF, VE, PBCF
Containerships 2000–2999 TEU	OTB, MEAT, OWF, VE
Bulkers 35–59999 DWT	MEAT, OTB, WED, OWF
Gas Tankers <49999 CBM	LNG, OWF, MEAT, PBCF, OTB, VE, FR

Table 7
Pareto and MCE Matrix - Containerships 8000+ TEU for cost-effective MMs (Baseline MACC Values).

MM	OTB	MEAT	OWF	VE	PBCF	Ranking	MCE	Final Ranking
OTB		YES	NO	YES	YES	2nd		2nd
MEAT	NO		NO	YES	EQUAL	3rd	MC = −200 k\$2020 ME = 2060 MT CO_2	4th
OWF	YES	YES		YES	YES	1st		1st
VE	NO	NO	NO		NO	4th		5th
PBCF	NO	EQUAL	NO	YES		3rd	MC = −192 k\$2020 ME = 2472 MT CO_2	3rd

YES: The MM dominates its counterpart.
NO: The MM is dominated by its counterpart.
EQUAL: The MM neither dominates nor is dominated by its counterpart.

Table 8
Final Results for all vessel categories.

Vessel Category Final Ranking	Container Ship 8000+ TEU	Containership 2000–2999 TEU	Bulkers 35–59999 DWT	Gas Tankers <49999 CBM	Fleet Average
1st	OWF	OWF	WED	LNG	
2nd	OTB	OTB	MEAT	OWF	
3rd	PBCF	MEAT	OWF	FR	
4th	MEAT	VE	OTB	PBCF	
5th	VE			MEAT	
6th				VE	
7th				OTB	
Cumulative Emission Reduction compared to the category's average emissions	15%	12%	11%	40,5%	
Cumulative Emission Reduction compared to the fleet's average emissions	9.8%	2.17%	1%	4%	17%
Cumulative Average Net Cost Savings (k\$2020)	1125	249	57	798	2229

emission reduction with negative marginal costs, meaning that the Containerships 8000+ TEU could sail with zero CO_2 emissions. However, CCS is responsible for 82% of the total reduction potential. Since CCS does not reduce fuel consumption, this technology does not provide a return on investment without carbon taxation.

Table 5 provides information on the emissions savings potential of cost-effective MMs for all vessel categories under each sensitivity analysis scenario. It should be noted that when several correlated MMs are cost-effective, the Pareto and MCE analyses allow the final decision-making. The percentage indicates the reduction in emissions compared to the average emissions of each vessel category.

MMs which preserved their CE under all sensitivity analyses were further analysed using the final Pareto and MCE analyses. For example, in the case of Containerships 8000+ TEU, the following MMs were considered; OTB, MEAT, OWF, VE, WED, and PCBF, where WED and PBCF are correlated. Pareto analysis, amongst them, using the baseline MACCs' results was performed to determine which MM is the most suitable for further analysis. In this case, PBCF was selected. Table 6 specifies the sorted MMs for each vessel category based on this process.

4.3. Pareto and marginal CE analyses

This section provides the results of Pareto and MCE analyses for the sorted MMs, as shown in Table 6. For the Pareto Analysis, the values given in the baseline MACCs for cost and emissions savings of MMs were used. The MMs, with similar performance in the Pareto analysis, are further compared based on MCE resulting in a final overall ranking. Table 7 provides the Pareto and MCE matrix for Containerships 8000+ TEU. Appendix F provides the Pareto and MCE matrices for the other vessel categories.

The overall analysis suggests OWF as the most recommendable option for Containership 8000+ TEU. Based on the baseline MACCs, OTB is the most desirable option, which with the complete analysis, ranks second. VE has the lowest investment costs compared to all the other MMs. Even though it would have been expected that a private investor would seek the solution with the lowest costs, an in-depth analysis reveals that other more costly MMs perform much better in an external unpredictable economic and political system. PBCF results in larger emissions savings and lower cost savings compared to MEAT. The MCE analysis revealed a difference of 19\$ per additional MT CO_2 abated when implementing PBCF instead of MEAT. MCE is below the threshold of 30\$/MT CO_2, which is equal to a potential carbon price. Therefore, PBCF is preferred over MEAT.

4.4. Summary of results

Table 8 provides an overview of the MMs that should be prioritised for each vessel category based on the overall analysis proposed in this paper. The table also provides information regarding the emission reduction potential compared to the vessel category's average emissions and compared to the fleet's average emissions if all proposed MMs are applied to all vessels under each vessel category.

Based on the MMs proposed in Table 8 and the baseline MACCs for each category, Containership 8000+ TEU can achieve a 15% reduction of CO_2 emissions in 2030 compared to the 2019 baseline at marginal costs <0 \$/MTCO_2. Comparatively, Containerships 2000–2999 TEU can achieve a 12% reduction, Bulkers 11%, and Tankers 40.5%. If the full potential is realized in all categories, the company can achieve at marginal costs <0 \$/MTCO_2 an overall 17% CO_2 emissions savings in 2030 from the examined fleet's average CO_2 emissions baseline.

Compared to the baseline MACCs results (cf. Table 6), Gas Tankers still ranks first as the category with the most significant emission reduction potential compared to the category's average emissions. Containerships 8000+ TEU experience a decrease of 7.4% and rank second. Containerships 2000–2999 TEU shift from the initially second place (36.3%) to the third place (12%). The largest decrease in emission savings is found in this category. The sensitivity analysis of fuel price halving on Containerships 2000–2999 TEU led to significant changes in the MMs CE. Half of the MMs, which initially provided a return on investment, acquired positive marginal abatement costs. Bulkers experience a decrease of 2% compared to the baseline MACCs and rank last.

The Containerships 8000+ TEU ranks first in terms of average cost savings followed by Tankers, Containerships 2000–2999 TEU, and Bulkers. This ranking is the same as in the case of baseline results (cf. Table 4). However, there is a decrease of 449 k $2020 of the cumulative average net cost savings since several MMs are excluded.

It must be underlined that these results are on an average basis. Therefore, the number of vessels within one category might results in higher or lower cost and emission savings compared to another category. If the company aims at prioritising its investments towards a specific vessel category, the number of vessels in each category should be considered. The analysis was performed for specific age range, and it is essential to include only the vessels within the examined age range. Table 8 provides an example of how the prioritisation of the vessel categories may alter when the emission reduction of each vessel category is compared to the fleet's average emissions.

5. Discussion

Most MACCs used for the shipping sector followed a social planner perspective by using social discount rates (Kesicki and Strachan, 2011). Hence, they dealt with larger fleets, like the European or world fleet, with the overall goal to provide decarbonisation policies to social planners. In contrast, this study employed a private perspective aiming at capturing the real market behaviour. The case company endorsed the discount rate used in this study, and therefore, reflects the company's real risks and required return on investment.

At the same time, other studies used data related to the vessels' operations from online databases such as the IMO's databases or Automatic Identification Systems (Eide et al., 2013; Schwartz et al., 2020). The input data used in this study are representative of the actual vessels' operations, and therefore the results are well-grounded. Fewer assumptions were needed regarding the vessel's time at port and sea, fuel types and consumption, emission factors, etc., and therefore the results are more objective.

The intertemporal uncertainties were considered through sensitivity analyses. Researchers recognized sensitivity analysis as a way to deal with the uncertainty of temporally fluctuating parameters such as the fuel price and the carbon tax (Faber et al., 2011; Heitmann and Peterson, 2012). The sensitivity analyses performed in former studies aimed at identifying which MMs and under which circumstances could become cost-effective. What distinguishes this study's approach is the use of the sensitivity analyses for the prioritisation of MMs. The recommended MMs are only those, which maintained their CE under all sensitivity analyses.

Another main shortcoming of MACCs is the ranking of MMs with negative marginal abatement costs. This study combines methods proposed by previous studies to rank the MMs. Following the sorting of MMs based on the sensitivity analyses, Pareto principles were applied to compare the costs and emissions savings. In the case of equally ranked MMs in the Pareto analysis, the MCE methodology was applied. The combination of the sensitivity analysis, the Pareto principles, and the MCE methodology, enable us to appropriately rank the MMs.

The produced results highlight that the prioritisation based on mere CE is not appropriate. The number of cost-effective MMs proposed in the final ranking (Table 8) is smaller due to; a) the selection of only one of the correlated MMs by using Pareto and MCE analyses, and b) the exclusion of the MMs, which do not maintain their CE under all sensitivity analyses. The remaining MMs underwent the Pareto and MCE analyses to be prioritised based on their net cost savings and emission savings. Hence, it is evident that not only the number but also the ranking of MMs differs. The total emission savings and the total cost savings per vessel category, due to the implementation of the proposed cost-effective MMs, are lower compared to the baseline MACCs.

Kesicki and Strachan (2011) stated that the lack of transparency in the assumptions made when dealing with the MACCs concept could affect the confidence level in the results. To enhance the confidence for decision-making, all data used, and assumptions made were explicitly mentioned. Overall, this study adds to the state-of-the-art shipping related MACCs through the employment of a private perspective using robust input data, gathered by an established ship-management company, which is transparently disclosed. Additionally, it provides the overall MACCs literature with a comprehensive way of treating the ranking of cost-effective MMs.

6. Conclusions

The primary goal of this study was to support the decarbonisation journey of a globally operating and well-established ship-management company through the prioritisation of CO_2 emissions MMs for its fleet. Based on the extensively used MACCs methodology coupled with Pareto and MCE analyses, a reliable comparison amongst several MMs proved possible. The combination of the previously explored methods led to the increased robustness of MACCs.

Three Containerships 8000+ TEU, three Containerships 2000–2999 TEU, two Bulkers 35000–59999 DWT, and two Gas Tankers <49999 CBM were explored. MACCs were developed for each vessel category using 2019 as the baseline and 2030 as target year. It should be noted that the average values of CE and annual CO_2 emissions reduction for each MM of vessels within the same category were used. Sensitivity analyses regarding fuel prices' doubling and halving and carbon taxation, allowed the initial sorting of MMs. Only the MMs able to maintain their cost-effectiveness under all sensitivity analyses were further analysed. The Pareto and MCE analyses, where the MMs were compared on their costs and emissions savings, allowed for a final ranking.

The results indicate that operational and technical MMs are more cost-effective options than alternative energy fuels. The company can achieve 15% CO_2 emission reduction in Containerships 8000+ TEU, 12% in Containerships 2000–2999 TEU, 11% reduction in Bulkers, and 40.5% reduction in Gas Tankers in negative marginal abatement costs compared to each category's average emissions. The reasons for the significant difference of Gas Tankers are (1) more MMs remain cost-effective under the sensitivity analyses, and (2) Gas Tankers are LNG-ready vessels, therefore LNG becomes a cost-effective option. Notably, if the cost-savings were allocated for further instalments of not cost-effective MMs, CCS could become a cost-effective option. However, both LNG and CCS should be mid-term solutions, as they do not lead to fossil fuels' independence.

Exploring the upper and lower limits of the abatement potentials rather than the average values and investigating the sensitivity of the results in other factors, such as the MM's learning effect, may provide interesting insights. In addition, extending this research by exploring how the sequence of MMs' implementation or the co-benefits and side-effects of MMs might influence the results is suggested. Incorporating such factors in our research work could further increase the MACCs robustness.

CRediT authorship contribution statement

Kyprianidou Irena: Methodology, Investigation, Writing Draft, Visualization. **Worrell Ernst:** Supervision. **Charalambides G. Alexandros:** Writing – review & editing, Supervision.

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.

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Appendix A. Table of Data

Table 9
Table of Data

MM	Vessel Type	MM Lifetime	Investment Costs ($2020)	Operational Costs ($2020)	Abatement Potential (%)	Relevant Engine
Operational Measures						
VE	Containership 8000+ TEU	5	10,683	5371	1.4	Main Engine
	Containership 2000–2999 TEU		10,683	5371	1.4	
	Bulkers 35000–59999 DWT		10,683	5341	2.5	
	Gas Tankers −49999 CBM		10,683	5341	2.5	
OTB	Containership 8000+ TEU	25	26,707	/	4	Main Engine
	Containership 2000–2999 TEU		26,707	/	4	
	Bulkers 35000–59999 DWT		26,707	/	1.5	
	Gas Tankers −49999 CBM		26,707	/	1.5	
PM	Containership 8000+ TEU	25	219,468	8593	0.8	Main Engine
	Containership 2000–2999 TEU		74,433	8593	1.1	
	Bulkers 35000–59999 DWT		32,687	8593	1.1	
	Gas Tankers −49999 CBM		9809	8593	1.1	
Technical Measures						
OWF	Containership 8000+ TEU	25	292,620	/	5	Total
	Containership 2000–2999 TEU		99,181	/	5	
	Bulkers 35000–59999 DWT		87,170	/	3	
	Gas Tankers −49999 CBM		13,080	/	3	
AL	Containership 8000+ TEU	25	2,974,578	10,683	5	Main Engine
	Containership 2000–2999 TEU		1,235,536	10,683	3	
	Bulkers 35000–59999 DWT		1,015,983	10,683	7	
	Gas Tankers −49999 CBM		1,114,064	10,683	7	
IPR	Containership 8000+ TEU	25	7,803,145	/	4	Total
	Containership 2000–2999 TEU		2,644,731	/	4	
	Bulkers 35000–59999 DWT		1,162,214	/	4	
	Gas Tankers −49999 CBM		348,801	/	4	
PBCF	Containership 8000+ TEU	25	522,757	/	3	Total
	Containership 2000–2999 TEU		354,415	/	3	
	Bulkers 35000–59999 DWT		79,804	/	3	
			43,169	/	3	

(continued on next page)

Table 9 (*continued*)

MM	Vessel Type	MM Lifetime	Investment Costs ($2020)	Operational Costs ($2020)	Abatement Potential (%)	Relevant Engine
	Gas Tankers −49999 CBM					
CRP	Containership 8000+ TEU	25	2,748,685	32,224	7	Main Engine
	Containership 2000–2999 TEU		1,337,205	32,224	7	
	Bulkers 35000–59999 DWT		917,201	21,482	7	
	Gas Tankers −49999 CBM		811,457	21,482	7	
FC	Containership 8000+ TEU	25	2,837,295	5371	10	Auxiliary Engine
	Containership 2000–2999 TEU		1,820,638	5371	10	
	Bulkers 35000–59999 DWT		596,138	5371	10	
	Gas Tankers −49999 CBM		1,063,382	5371	10	
WHR	Containership 8000+ TEU	25	10,148,633	32,224	8	Main Engine
	Containership 2000–2999 TEU		10,148,633	21,482	5	
	Bulkers 35000–59999 DWT		6,486,700	10,741	3	
	Gas Tankers −49999 CBM		5,429,258	10,741	4	
MEAT	Containership 8000+ TEU	25	48,072	/	2.5	Total
	Containership 2000–2999 TEU		32,224	/	2.5	
	Bulkers 35000–59999 DWT		26,853	/	2.5	
	Gas Tankers −49999 CBM		32,224	/	2.5	
WED	Containership 8000+ TEU	25	222500	/	2	Total
	Containership 2000–2999 TEU		222500	/	2	
	Bulkers 35000–59999 DWT		127500	/	4.5	
	Gas Tankers −49999 CBM		127500	/	3	
CCS	Containership 8000+ TEU	25	668,700	694,980	100	Main Engine (Only CO_2 reduction, no fuel)
	Containership 2000–2999 TEU		138,687	145,020	100	
	Bulkers 35000–59999 DWT		58,562	69,390	100	
	Gas Tankers −49999 CBM		80,863	43,290	100	
Alternative Energy Sources						
CI	Containership 8000+ TEU	10	560,845	Costs for electricity use at port	100	Auxiliary Engine (Fuel Consumed while at berth)
	Containership 2000–2999 TEU		560,845		100	
	Bulkers 35000–59999 DWT		1,879,715		100	
	Gas Tankers −49999 CBM		563,914		100	
SP	Bulkers 35000–59999 DWT	10	1,471,548	/	1	Auxiliary Engine
	Gas Tankers −49999 CBM		1,653,645	/	1.5	
Kites	Bulkers 35000–59999 DWT	25	1,062,307	79,055	8.9	Main Engine
	Gas Tankers −49999 CBM		554,247	30,935	12.3	
FR[a]	Bulkers 35000–59999 DWT	25	1,286,963	/	15.7	Main Engine
	Gas Tankers −49999 CBM		491,468	/	8.1	
LNG[b]	Containership 8000+ TEU	25	50,520,000	Costs of fuel replacement based on fuel price	25[c]	Main Engine
	Containership 2000–2999 TEU		7,704,000		25	

(continued on next page)

Table 9 (*continued*)

MM	Vessel Type	MM Lifetime	Investment Costs ($2020)	Operational Costs ($2020)	Abatement Potential (%)	Relevant Engine
	Bulkers 35000–59999 DWT		7,200,000		25	
	Gas Tankers –49999 CBM		/[d]		25	
HFC[e]	Containership 8000+ TEU	FC - 25 Stack - 3	547,084,465	Costs of fuel replacement based on fuel price and costs for stack replacement	100	Auxiliary Engine
	Containership 2000–2999 TEU		120,203,840		100	
	Bulkers 35000–59999 DWT		54,888,774		100	
	Gas Tankers –49999 CBM		76,233,950		100	
BF	Containership 8000+ TEU	25	/	Costs of fuel replacement based on fuel price	85[f]	Total
	Containership 2000–2999 TEU		/		85	
	Bulkers 35000–59999 DWT		/		85	
	Gas Tankers –49999 CBM		/		85	

[a] The abatement potential takes into account the energy needed to support the FR.
[b] 3% of HFO allocated to the main engine will not be replaced as it is used as ignition fuel (Laursen, 2016).
[c] (Koren et al., 2010; DNV GL – DNV GL - Maritime, 2019).
[d] Gas Tankers are LNG ready vessels.
[e] Investment costs for fuel cells and on-board storage of hydrogen.
[f] DNV GL – DNV GL - Maritime, 2019.

Appendix B. Data for Fuel Types

Table 10
Data for Fuel Types

Fuel Type	Energy Content (GJ/MT)	Source	Fuel Price ($/MT)	Source
HFO	40.2	IMO (2016)	300	Ship & Bunker, (2020[a])
LSFO	41	Ship & Bunker, (2020[b])	450	Ship & Bunker, (2020[a])
MDO	43	IMO (2016)	350	Ship & Bunker, (2020[a])
LNG	48	IMO (2016)	150	Alternative Fuels Insight Platform (2020)
Hydrogen	120	Moller et al. (2017)	4250	Hydrogen Council (2020)
Biofuels	37.2	Alternative Fuels Insight Platform (2020)	820	Alternative Fuels Insight Platform (2020)

Appendix C. Sensitivity Analyses MACCs for Containership 2000–2999 TEU

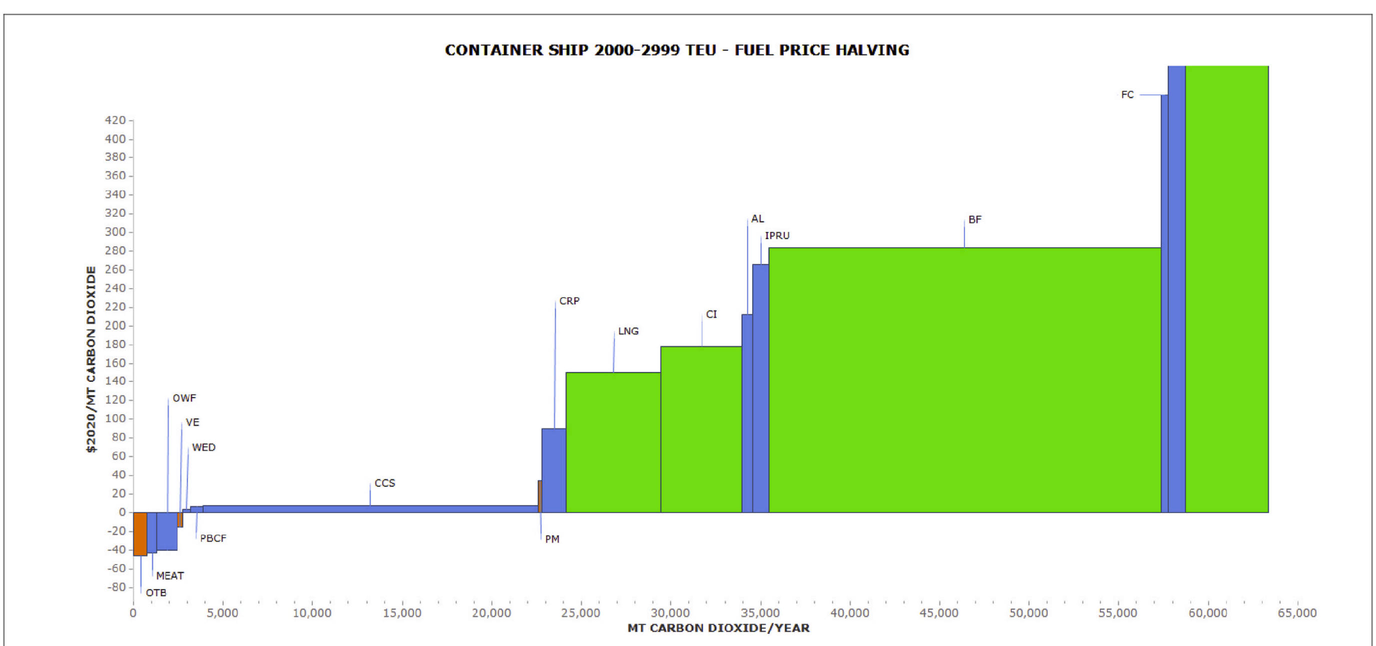

Fig. 9. MACC for Containership 2000–2999 TEU - Half Fuel Prices. *Orange: Operational Measures, Green: Alternative Energy Sources, Blue: Technical Measures.*

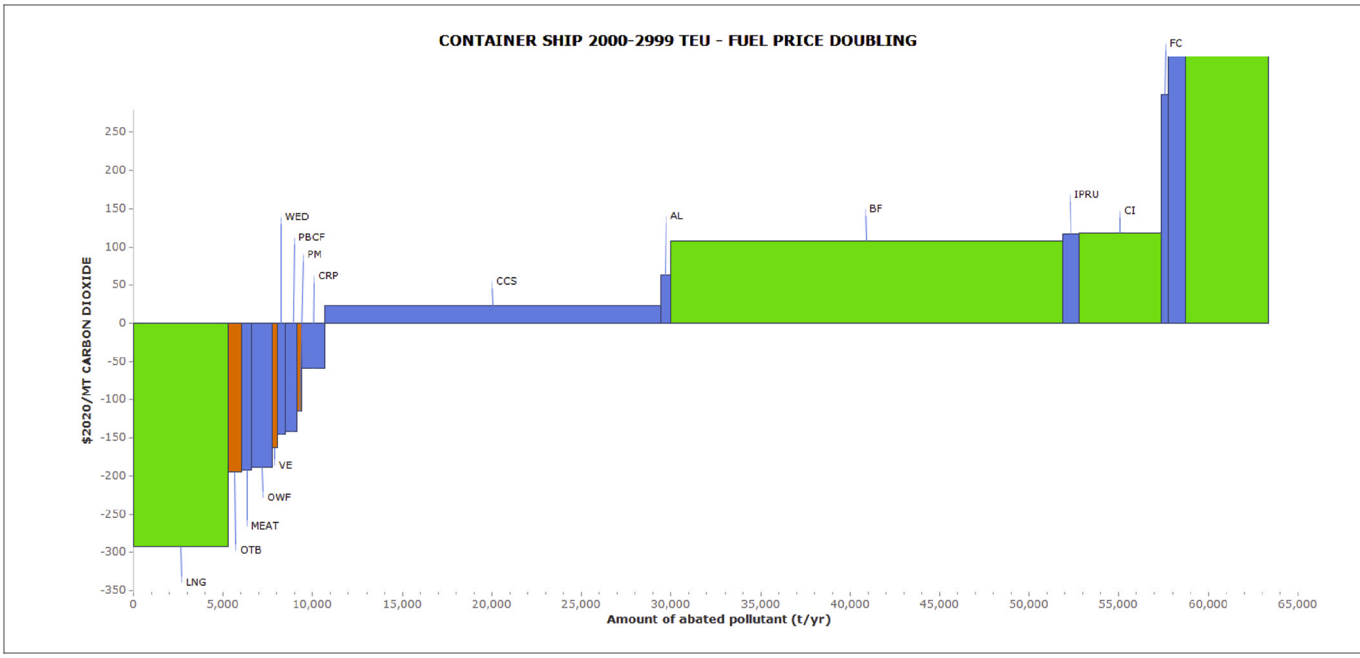

Fig. 10. MACC for Containership 2000–2999 TEU - Double Fuel Prices. *Orange: Operational Measures, Green: Alternative Energy Sources, Blue: Technical Measures.*

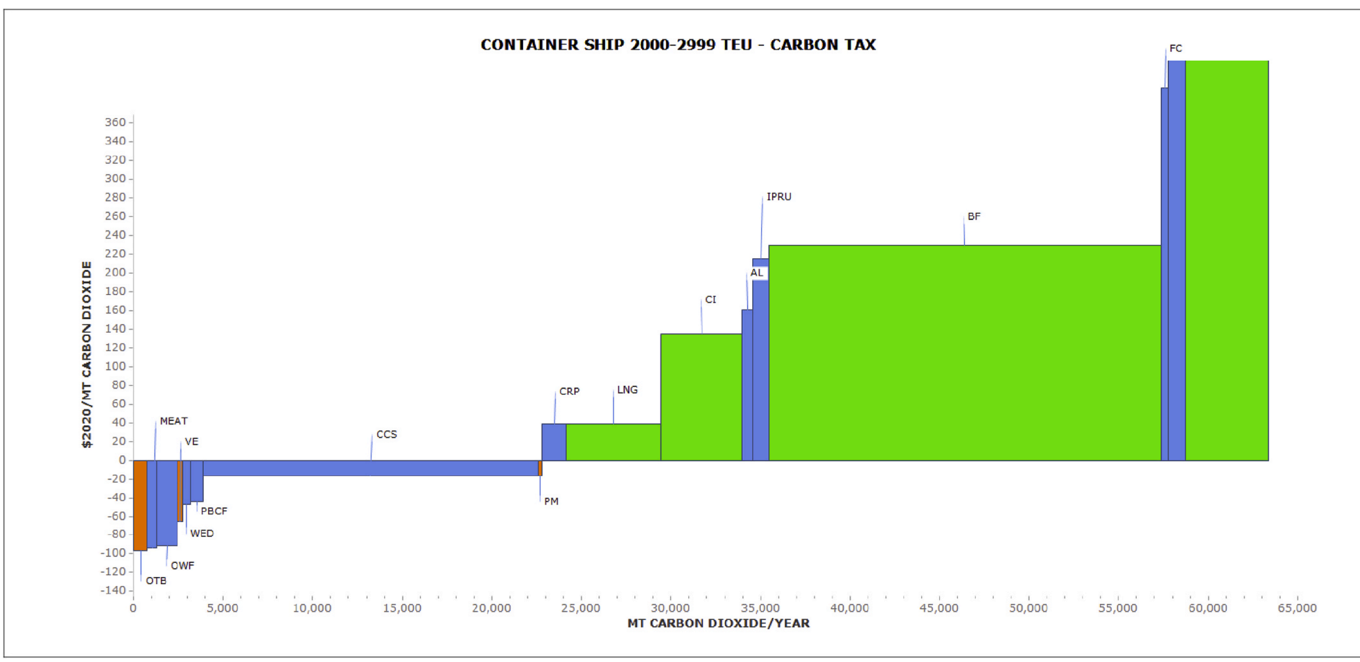

Fig. 11. MACC for Containership 2000–2999 TEU - Carbon Tax. *Orange: Operational Measures, Green: Alternative Energy Sources, Blue: Technical Measures.*

Appendix D. Sensitivity Analyses MACCs for Bulkers 35000–59999 DWT

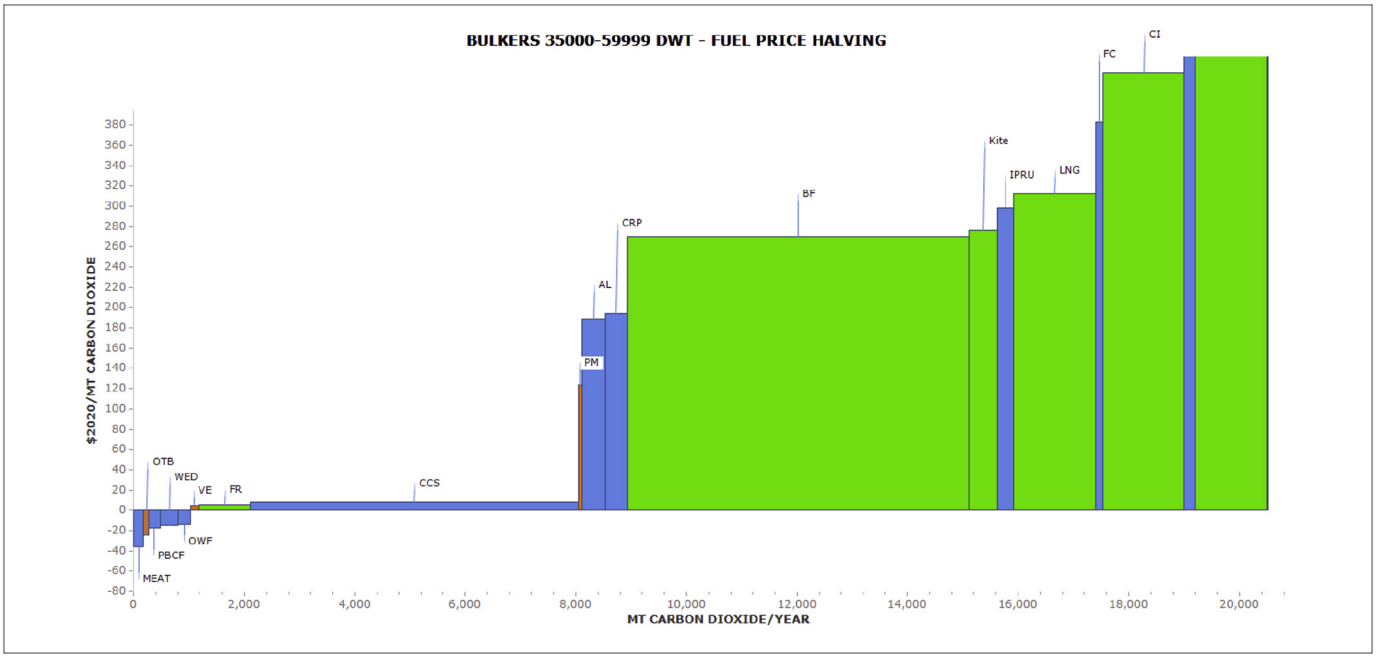

Fig. 12. MACC for Bulkers 35000–59999 DWT - Half Fuel Prices. *Orange: Operational Measures, Green: Alternative Energy Sources, Blue: Technical Measures.*

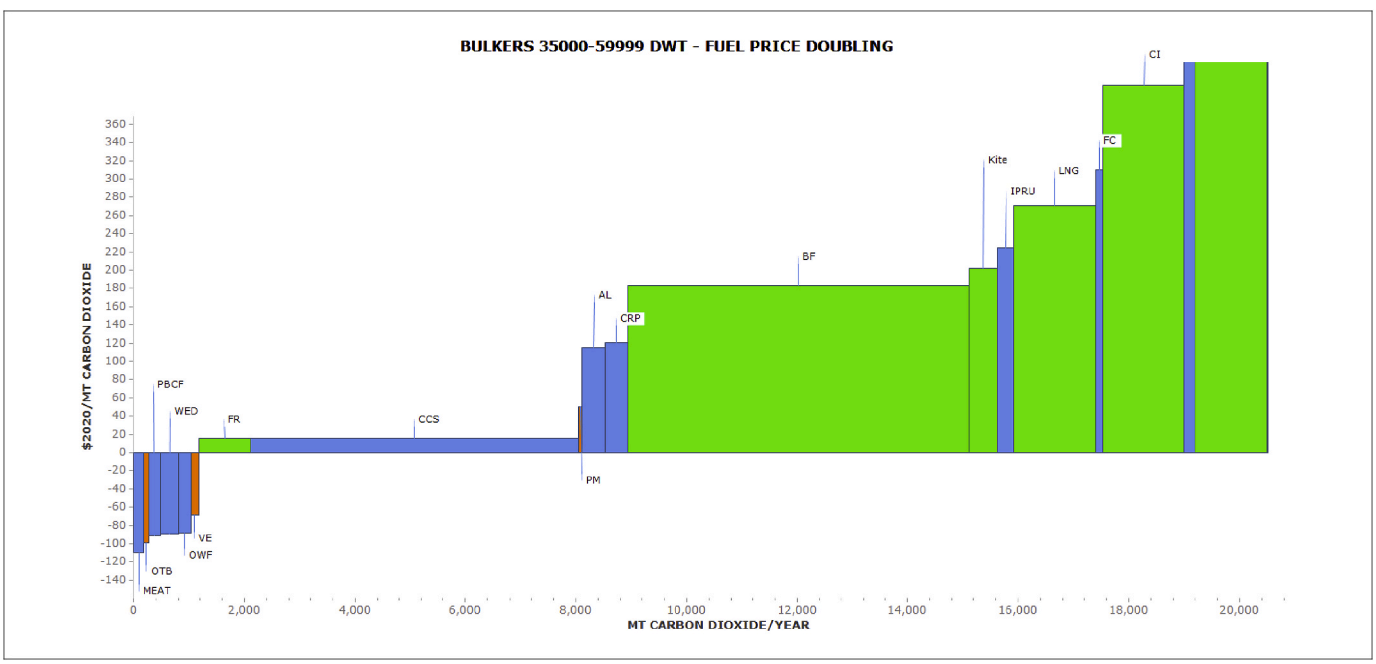

Fig. 13. MACC for Bulkers 35000–59999 DWT - Double Fuel Prices. *Orange: Operational Measures, Green: Alternative Energy Sources, Blue: Technical Measures.*

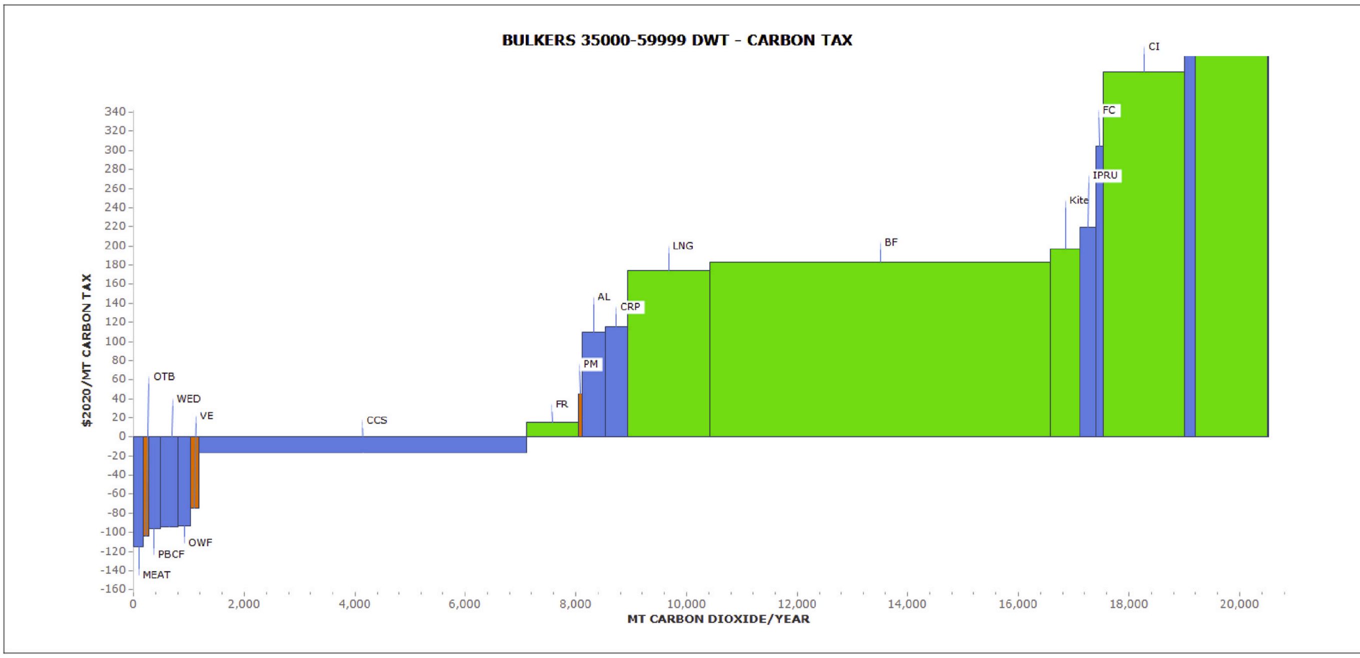

Fig. 14. MACC for Bulkers 35000–59999 DWT - Carbon Tax. *Orange: Operational Measures, Green: Alternative Energy Sources, Blue: Technical Measures.*

Appendix E. Sensitivity Analyses MACCs for Gas Tankers <49999 CBM

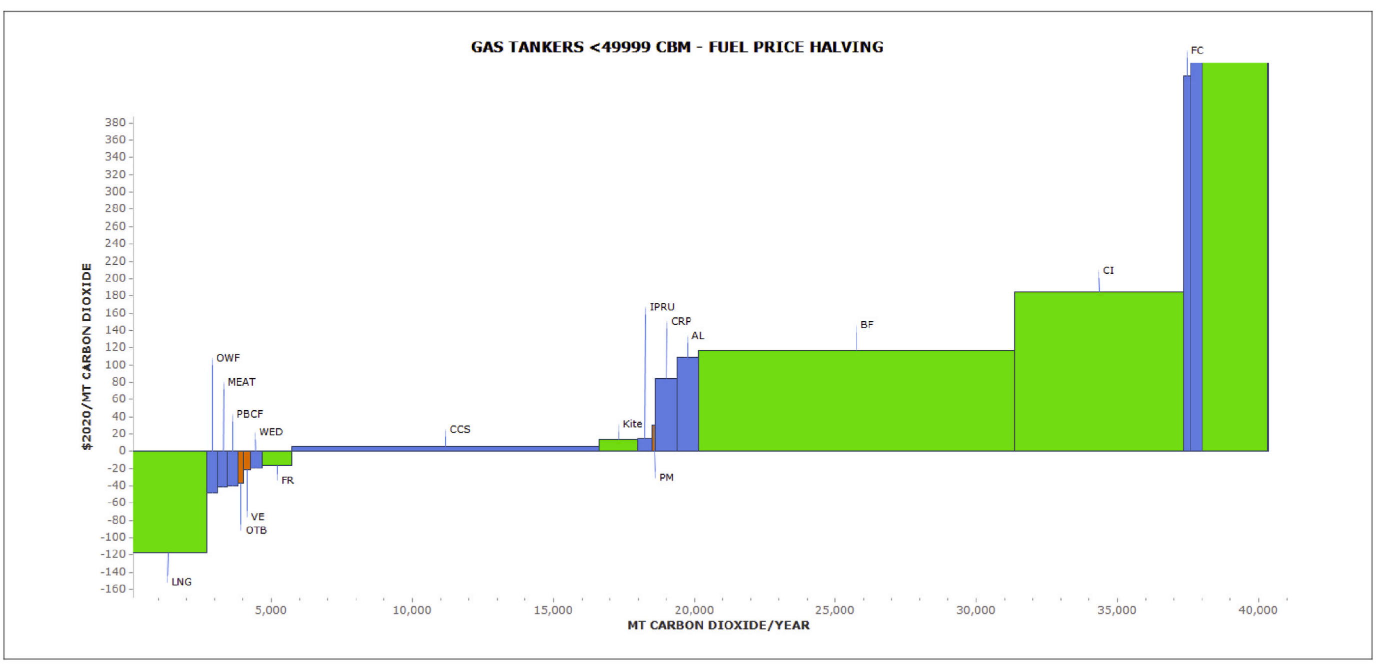

Fig. 15MACC for Gas Tankers <49999 CBM - Half Fuel Prices. *Orange: Operational Measures, Green: Alternative Energy Sources, Blue: Technical Measures.*

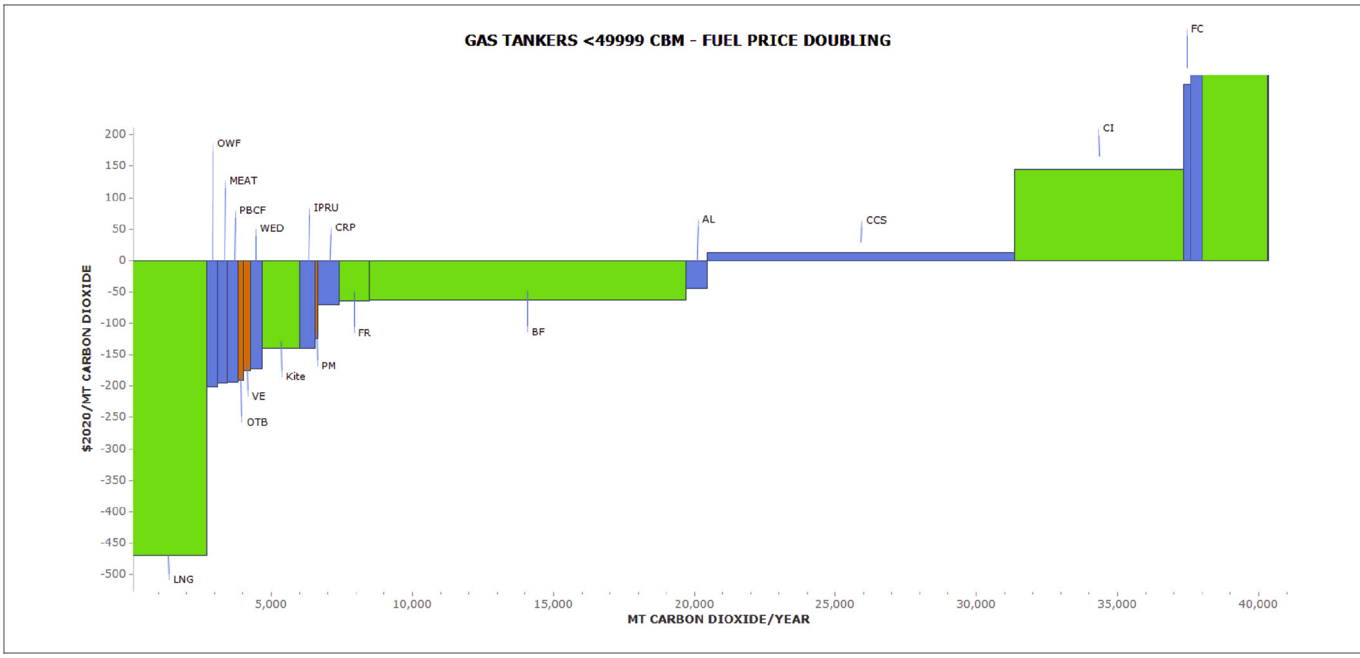

Fig. 16. MACC for Gas Tankers <49999 CBM - Double Fuel Prices. *Orange: Operational Measures, Green: Alternative Energy Sources, Blue: Technical Measures.*

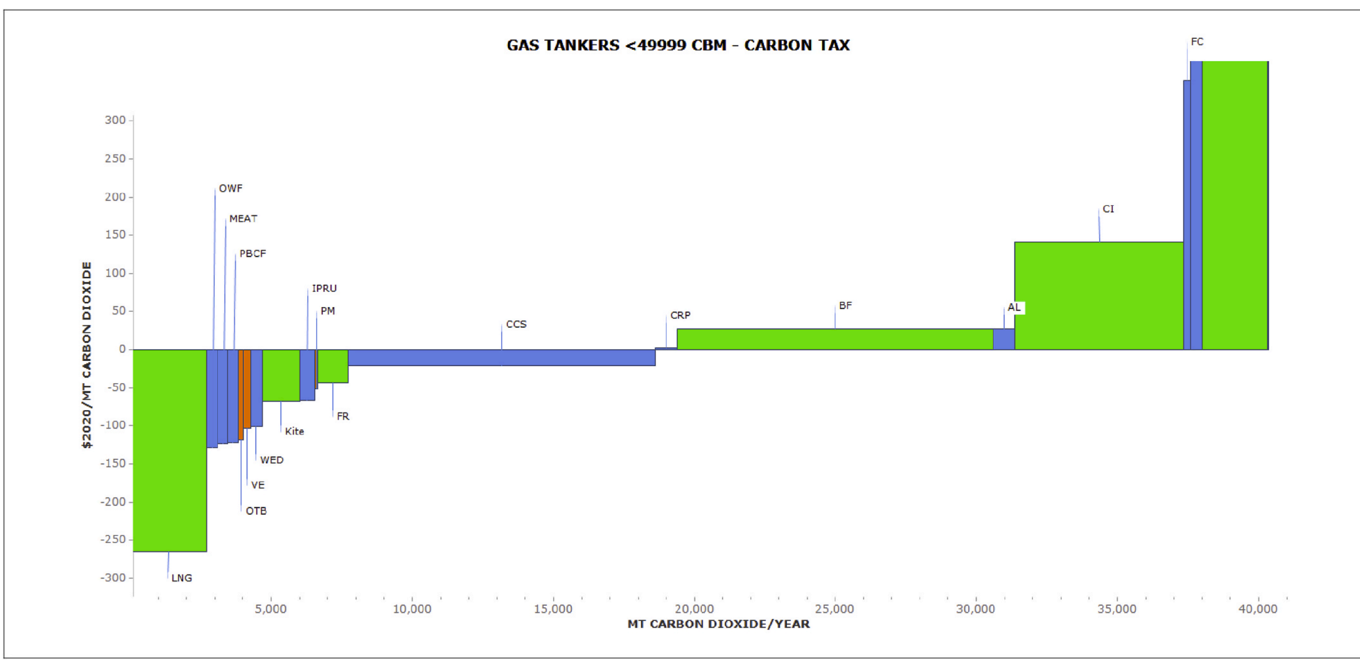

Fig. 17. MACC for Gas Tankers <49999 CBM - Carbon Tax. *Orange: Operational Measures, Green: Alternative Energy Sources, Blue: Technical Measures.*

Appendix F. Pareto and MCE Analyses – Matrix per Vessel Category

Table 11
Containership 2000–2999 TEU - Pareto and MCE Matrix

MM	VE	OTB	OWF	MEAT	Final Ranking
VE	/	NO	NO	NO	4th
OTB	YES	/	NO	YES	2nd
OWF	YES	YES	/	YES	1st
MEAT	YES	NO	NO	/	3rd

Table 12
Bulkers 35000–59999 DWT - Pareto and MCE Matrix

MM	OTB	OWF	WED	MEAT	Ranking	MCE	Final Ranking
OTB	/	NO	NO	NO	3rd		4th
OWF	YES	/	NO	EQUAL	= 2nd	MC = - 13, 740 \$2020 ME = 217.56 MT CO_2	3rd
WED	YES	YES	/	YES	1st		1st
MEAT	YES	EQUAL	NO	/	= 2nd	MC = −15,392 \$2020 ME = 181.3 MT CO_2	2nd

Table 13
Gas Tankers <49999 CBM - Pareto and MCE Matrix

MM	VE	OTB	OWF	PBCF	MEAT	FR	LNG	Ranking	MCE	Final Ranking
VE	/	YES	NO	NO	NO	NO	NO	5th		6th
OTB	NO	/	NO	NO	NO	NO	NO	6th		7th
OWF	YES	YES	/	YES	YES	EQUAL	NO	2nd		2nd
PBCF	YES	YES	NO	/	YES	EQUAL	NO	3rd	MC = 36,327 \$2020 ME = 395.6 MT CO_2	4th
MEAT	YES	YES	NO	NO	/	NO	NO	4th		5th
FR	YES	YES	EQUAL	EQUAL	YES	/	NO	3rd	MC = −35,193 \$2020 ME = 1068.2 MT CO_2	3rd
LNG	YES	YES	YES	YES	YES	YES	/	1st		1st

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