Journal of
Marine Science
and Engineering

MDPI

Article

Study on Cost-Effective Performance of Alternative Fuels and Energy Efficiency Measures for Shipping Decarbonization

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Abstract: Within the context of global initiatives to address climate change, the shipping industry is facing increasingly intensified pressure to decarbonize. The industry is engaging in the exploration and implementation of greenhouse gas (GHG) emission reduction measures, including energy efficiency technologies and alternative fuels, with the objective of accelerating the progression towards greenhouse gas mitigation. The application of various GHG emission reduction measures usually requires different levels of investment costs, and economic feasibility is a key factor influencing policy formulation and investment decisions. In this regard, this paper developed a cost-effective model for energy efficiency measures and alternative fuels based on the marginal abatement cost (MAC) methodology. This model can distinguish the differences between energy efficiency measures and alternative fuels in terms of Tank-to-Wake emissions and Well-to-Wake emissions in the GHG emission evaluation system. By taking typical ship types with significant emission contributions as study cases, i.e., bulk carriers (61–63K DWT), container ships (8000 TEU), product tankers (115K DWT), crude oil tankers (315–320K DWT), and Ro-Ro passenger ferries (3500 DWT), the GHG abatement cost-effective performance of major categories of measures such as operational measures, technical measures, renewable energy sources, and alternative fuels were calculated. According to the MAC results, the marginal abatement cost curves were plotted based on the ranking of energy efficiency measures and alternative fuels, respectively. The impacts of bunker fuel prices and carbon market prices on the cost-effectiveness were analyzed. The research results provided the GHG abatement potential of the integrated application of cost-effective energy efficiency measures, the cost-effectiveness ranking of alternative fuels, and the carbon emission price expected to bridge the price gap between alternative fuels and conventional bunker fuel. The presented methodology and conclusions can be used to assist shipping companies in selecting emission reduction measures, and to support maritime authorities in developing market-based measures.

Keywords: greenhouse gas abatement measures; energy efficiency measures; alternative fuels; marginal abatement cost curves; cost-effectiveness

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Citation: Tu, H.; Liu, Z.; Zhang, Y. Study on Cost-Effective Performance of Alternative Fuels and Energy Efficiency Measures for Shipping Decarbonization. *J. Mar. Sci. Eng.* **2024**, *12*, 743. https://doi.org/10.3390/jmse12050743

Academic Editor: Theocharis D. Tsoutsos

Received: 9 April 2024
Revised: 27 April 2024
Accepted: 27 April 2024
Published: 29 April 2024

1. Introduction

In the context of addressing climate change collectively across nations and industries globally, the international shipping industry is accelerating the process of reducing greenhouse gas emissions. In July 2023, the International Maritime Organization (IMO) adopted the 2023 IMO Strategy on the Reduction of GHG Emissions from Ships at the 80th session of the Marine Environment Protection Committee (MEPC 80), setting out a new goal of reaching net-zero GHG emissions by or around 2050 as well as taking up zero or near-zero GHG emission technologies, fuels, and/or energy sources to represent at least 5%, striving for 10%, of the energy used by international shipping by 2030 [1].

In response to the increasingly stringent greenhouse gas emission reduction targets, the industry is actively developing and applying emission reduction measures, including technical energy efficiency measures, operational energy efficiency measures, and low-carbon/zero-carbon alternative fuels [2]. In policy formulation and investment decisions concerning greenhouse gas reduction measures, the emissions reduction potential and the implementation cost are two crucial considerations [3]. The industry seeks to prioritize measures with high emissions reduction potential and low cost implications, but in practice, these two factors are often challenging to balance. In other words, measures with a high emissions reduction potential often involve significant costs, while those with low implementation costs typically offer a limited emissions reduction potential. Therefore, policy makers and investment decision makers are confronted with the challenge of selecting suitable and cost-effective carbon reduction measures [4–6]. To this end, marginal abatement costs (MACs) and marginal abatement cost curves (MACCs) have been widely used to assess the cost-effectiveness of various greenhouse gas emission reduction measures for ships [7–9]. The marginal abatement cost refers to the cost of reducing one additional unit of emission. Based on the relationship between marginal abatement cost and emission reduction potential, MACC can be plotted [10,11]. With MACC to represent the economic feasibility of various emission reduction measures, it is possible to rank all the measures according to their cost-effectiveness and propose priority measures for implementation. The MACC method has become an effective analytical tool providing support for policy formulation and investment decisions [12–14].

1.1. Literature Review

According to the relevant literature on the application of the MACC method in reducing greenhouse gas emissions in the shipping industry, there are typically two main methods used to develop MACC models [15]. In the first method, the MACC models are based on the cumulative assessment of the integrated application of various emissions reduction measures by a fleet, generating a linear cost-effectiveness trend line corresponding to the abatement potential for a specific year. The first method is primarily applied at the macro-analysis level of fleets from companies, countries, or globally. In the second method, the MACC models are based on an individual assessment of various emission reduction measures applied in a specific ship, with the cost-effectiveness and abatement potential of each measure assessed in isolation. Subsequently, the emission reduction measures are ranked from lowest to highest to cost-effectiveness, forming step-form curves that represent the MAC of the abatement measures over their whole lifetime. The second method is primarily applied to the micro-level analysis of individual vessels adopting different emissions reduction measures. A brief literature review extracted from various studies is presented in Table 1, with considerations in terms of method category, application ship types, and emission reduction measures to review the related studies.

Previous research indicates that, since 2009, both industry and academia have carried out a series of studies on marginal abatement costs in the field of greenhouse gas emissions reduction for ships. Viewed from the perspective of the MACC method, research reports from the IMO and related maritime consulting agencies typically use the first MACC method, aiming to investigate the overall abatement potential and cost-effectiveness of the global fleet in implementing greenhouse gas emission reduction measures, and thus assess the global fleet's emission reduction potential and establish rational and feasible emission reduction targets. For shipping companies, maritime authorities, and relevant research scholars, there is a preference to focus on the cost-effectiveness of applying different emissions reduction measures on specific vessel types. This assists in investment decisions and regulatory policy making and hence typically adopt the second MACC method. Viewed from the perspective of the investigated abatement measures, the development trend of research hotspots in emissions reduction measures is closely related to the greenhouse gas emissions reduction pathways and technology development in the shipping industry. In recent years, with the strengthening of emissions reduction targets in shipping, the research focus has gradually shifted towards alternative fuels.

Table 1. Literature review on previous MACC studies of GHG abatement measures for ships.

MACC Method	Country/Organization	Year	Application Ships	Abatement Measures	Ref.
First type: cumulative assessment for cost-effectiveness of integrated application of various abatement measures by a fleet (linear cost-effectiveness trend line)	IMO	2009	Global fleet (14 ship types)	25 energy efficiency measures (10 groups)	[16]
	Netherlands	2009	Global fleet (14 ship types)	29 energy efficiency measures (12 groups)	[17]
	IMO	2014	Global fleet (14 ship types)	22 measures (including LNG and biofuel)	[18]
	IMO	2020	Global fleet (13 ship types)	34 energy efficiency measures (3 groups) + 10 alternative fuels	[19]
	Norway	2011	Global fleet (7 ship types)	25 energy efficiency measures (3 groups) + LNG	[20]
	United States of America	2012	Global fleet (14 ship types)	12 energy efficiency measures (6 operational + 6 technical)	[21]
	Germany	2012	Global fleet (14 ship types)	22 energy efficiency measures (15 groups)	[22]
	China	2019	Global fleet (tankers, containers, and bulk carriers)	14 energy efficiency measures (5 optional + 9 technical)	[8]
Second type: individual assessment of various abatement measures applied in case ships (step-form cost-effectiveness curves)	Norway	2009	2 Case ships (74,000 DWT bulk carrier, 8000 TEU Container ship)	12 energy efficiency measures	[23]
	Organization for Economic Co-operation and Development and the International Transport Forum	2009	8500 TEU Container ship	Slow steaming	[24]
	Germany	2012	Container ship fleet	12 energy efficiency measures	[25]
	Netherlands	2015	10 Case ships	18 energy efficiency measures + 2 alternative fuels	[26]
	Singapore	2016	3 Case ships (bulk carrier, container ship, tanker)	14 energy efficiency measures (5 optional + 9 technical)	[27]
	Norway	2017	6 Case ships	8 alternative fuels	[28]
	China	2018	2 Case ships (feeder container ship, ferry)	LNG	[29]
	Czech	2020	9 Case ships	12 energy efficiency measures	[30]
	Norway	2020	4 Case ships	8 alternative fuels	[31]
	Cyprus	2021	4 Case ships	18 energy efficiency measures (3 groups) + 2 alternative fuels (LNG, biofuel)	[14]
	Germany	2022	Not specified	4 alternative fuels (LNG, methanol, ammonia, and hydrogen)	[9]
	Turkey	2022	Bulk carrier	Ammonia	[32]

1.2. Research Gaps and Limitations

Summarizing the previous literature in this field, although extensive studies have developed MACC models to investigate the cost-effectiveness and abatement potentials of representative greenhouse gas emission reduction measures, there are still some gaps and limitations in terms of abatement measures, GHG emission assessment methods, and market-based measure implications. Firstly, there is limited research focusing on both energy efficiency measures and alternative fuels. Currently, applying energy efficiency technologies will not be enough to meet the increasingly stringent emission reduction targets, and thus, the development trend is toward the integrated application of alternative fuels and energy efficiency measures to achieve a greater emission reduction potential [33]. Secondly, the international regulatory system for assessing greenhouse gas emissions from marine fuels is shifting from a vessel-based approach to a lifecycle approach. The MACC of marine alternative fuels calculated following the vessel-based approach will be no longer applicable to the upcoming lifecycle assessment method [34]. Thirdly, previous MACC studies did not adequately account for the influence of market mechanisms. The EU has currently introduced a package of market-based mechanisms to the shipping industry, including the Emissions Trading System (ETS) and FuelEU Maritime. At the IMO level, the carbon pricing mechanism linked to marine fuel GHG intensity is also under discussion. Therefore, it is necessary to investigate the impact of carbon pricing mechanism on the cost-effective performance of emission reduction measures.

1.3. Contribution of This Research

In view of these gaps and limitations, this paper develops a cost-effective performance model for typical energy efficiency measures and alternative fuels based on the second MACC method. The MACC model distinguishes between energy efficiency technologies and alternative fuels in the emission assessment system by using the Tank-to-Wake and Well-to-Wake approach, respectively. Moreover, the model also incorporates the influencing factor of the carbon pricing mechanism. Based on the MACC model, greenhouse gas emission reduction measures, including technological energy efficiency measures, operational efficiency measures, renewable energy utilization measures, and alternative fuels, are calculated and ranked for five typical vessel types: bulk carriers, container ships, product tankers, crude oil tankers, and Ro-Ro passenger ferries. Sensitivity analyses are carried out to analyze the impact of fuel prices on cost-effectiveness and to estimate the carbon emission pricing needed to bridge the cost gap between alternative fuels and traditional fuels. The proposed MACC models and results can provide insights into greenhouse gas emission reduction measure selection, investment decisions, and policy formulation in the shipping industry.

2. Methodology

2.1. Research Procedures

The MACC research requires determining each project's financial details and GHG abatement potential over the project's lifecycle. The research procedure as shown in Figure 1 comprises the five steps below:

- Conduct a comprehensive survey of various representative GHG abatement measures, and screen applicable measures for case study vessels.
- Develop a MAC model based on the survey data, and calculate the MAC of individual abatement measures.
- Rank the measures according to their cost-effectiveness, and construct a MACC based on the relationship between the MAC and the abatement potential of each measure.
- Perform a sensitivity analysis to investigate several input parameters' influence on the cost-effectiveness.
- Propose recommendations on the abatement measure application and policy development.

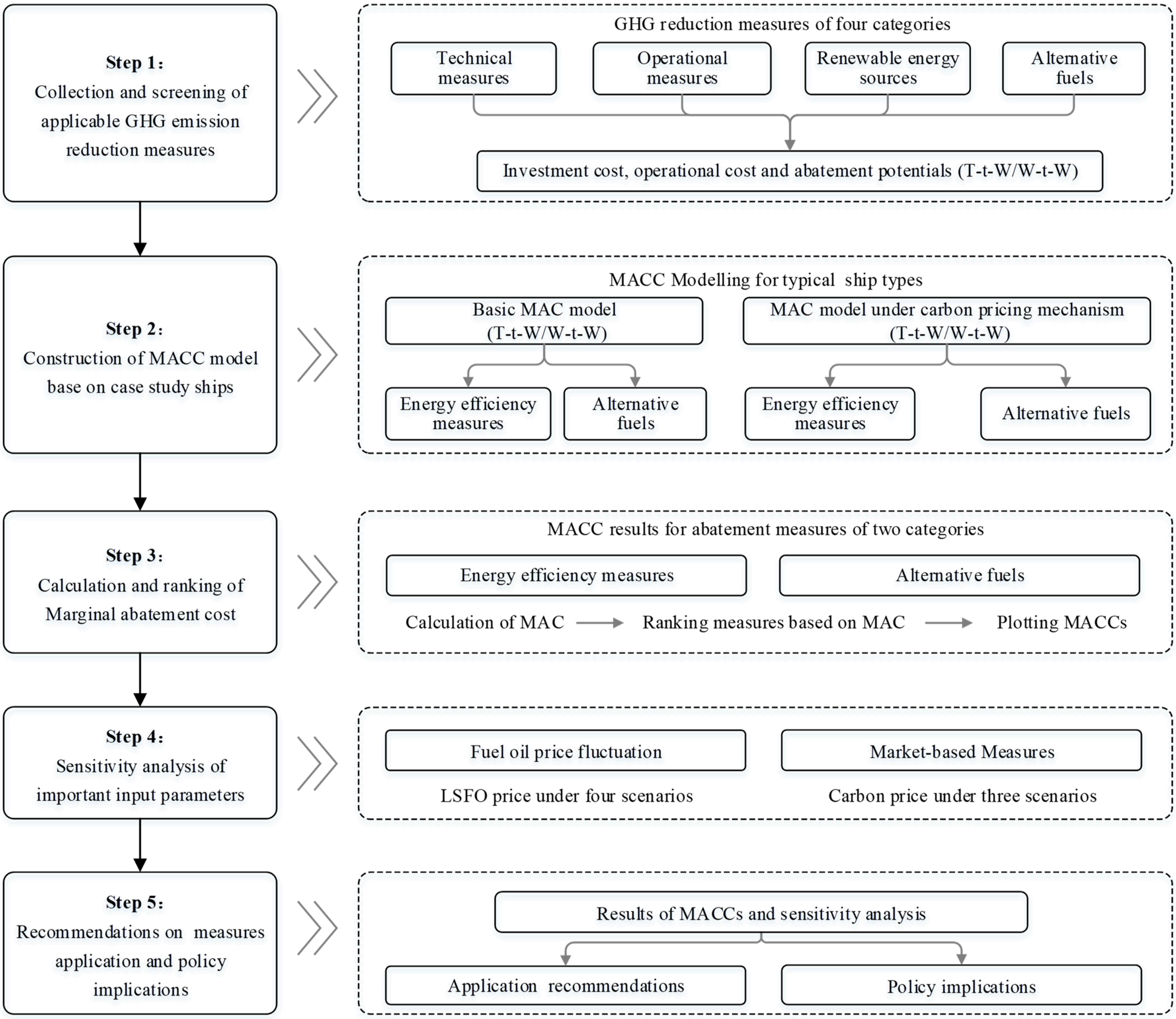


Figure 1. Research procedures of the MACC study.

2.2. Basic MAC Model

The method described in the IMO MEPC62 report is adopted in this paper to develop the MAC model for abatement measures [18]. The marginal abatement cost is defined as the quotient between net costs of implementing an abatement measure and its GHG emission abatement amount [7]. For the net costs, all costs of different categories need to be annualized for calculation [14,35]. Therefore, the MAC of an abatement measure can be calculated using the following equation:

$$MAC = \frac{\Delta NCOST}{\Delta CO_{2e}} \tag{1}$$

where

$\Delta NCOST$ represents the annual net cost of implementing an abatement measure compared with conventional ships (USD/year);

ΔCO_{2e} represents the annual GHG emission abatement amount (t CO_{2e}/MJ).

2.2.1. Net Cost

The net cost of implementing a mitigation measure can be defined as the following equation:

$$\Delta NCOST = IC + OC - CS \tag{2}$$

where

IC is the annualized investment cost of implementing the measure (USD/year);
OC is the operational cost related to using the measure (USD/year);
CS is the cost savings obtained by implementing the measure (USD/year).

The annualized investment cost can be calculated using the following equation:

$$IC = TC \times \frac{d}{1 - (1 + d)^{-L}} \tag{3}$$

where

TC is the total investment cost of implementing the measure;
d is the discount rate;
L is the lifetime of a vessel implementing the measure.

The operational cost needs to be calculated according to measure categories. For energy efficiency measures, the data for operational cost can be collected from the related literature. For alternative fuels, the operational costs are the primarily fuel costs. The cost function of using alternative fuels can be defined as the following equation:

$$OP = FP_{alt} \times FC_{LSFO} \times \frac{LHV_{LSFO}}{LHV_{alt}} \tag{4}$$

where

FP_{alt} is the price of the alternative fuel (USD/t);
FC_{LSFO} is the annual LSFO fuel consumption of the vessel (t/year);
LHV_{LSFO} and LHV_{alt} represent the lower heating value of LSFO and alternative fuel, respectively (MJ/kg).

The cost savings depend on the measure category:

$$CS = \begin{cases} FP_{LSFO} \times FC_{LSFO} \times AP & \text{for energy efficiency measures} \\ FP_{LSFO} \times FC_{LSFO} & \text{for alternative fuels} \end{cases} \tag{5}$$

where AP represents the abatement potential of energy efficiency measures (%).

2.2.2. Abatement Amount

The abatement amount of energy efficiency measures and alternative fuels are assessed based on the Tank-to-Wake and Well-to-Wake approaches, respectively. Therefore, the calculation of the abatement potentials of energy efficiency measures and alternative fuels should be distinguished. The GHG emission considered in this paper includes CO_2, CH_4, and N_2O, and they are accounted for based on the measurement unit of CO_2 equivalent [36].

The abatement amount for energy efficiency measures can be calculated using the following equation:

$$\Delta CO_{2e} = \begin{cases} GHG_{TtW} \times FC_{LSFO} \times LHV_{LSFO} \times AP_{eff} & \text{for energy efficiency measures} \\ GHG_{WtW} \times FC_{LSFO} \times LHV_{LSFO} \times AP_{alt} & \text{for alternative fuels} \end{cases} \tag{6}$$

where

GHG_{TtW} is the GHG emission factor of LSFO in the scope of Tank-to-Wake (g CO_{2e}/MJ);
GHG_{WtW} is the GHG emission factor of LSFO in the scope of Well-to-Wake (g CO_{2e}/MJ);
AP_{eff} is the abatement potential of the energy efficiency measure (%);

AP_{alt} is the abatement potential of the alternative fuel (%).

Based on the Well-to-Wake methodology in the IMO LCA guidelines [34], the Well-to-Wake GHG emission factor is calculated as follows:

$$GHG_{WtW} = GHG_{WtT} + GHG_{TtW} \tag{7}$$

where GHG_{WtT} is the GHG emission factor of LSFO in the scope of Well-to-Tank (g CO_{2e}/MJ).

The Well-to-Tank GHG emissions factor is calculated according to following equation:

$$GHG_{WtT} = e_{ec} + e_l + e_p + e_{td} - e_c - e_{sca} - e_{ccs} - e_{ccu} \tag{8}$$

where

e_{ec} is the emissions from the extraction or from the cultivation of raw materials, g CO_{2e}/MJ;
e_l is the annualized emissions from carbon stock changes caused by land-use change (over 20 years), g CO_{2e}/MJ;
e_p is the emissions from processing, including electricity generation, g CO_{2e}/MJ;
e_{td} is the emissions from transport and distribution, g CO_{2e}/MJ;
e_c is the emissions credits generated by biomass growth, g CO_{2e}/MJ;
e_{sca} is the emission savings from soil carbon accumulation via improved agricultural management, g CO_{2e}/MJ;
e_{ccs} is the emission savings from CO_2 capture and geological storage, g CO_{2e}/MJ;
e_{ccu} is the emission savings from CO_2 capture and utilization, g CO_{2e}/MJ.

The Tank-to-Wake GHG emission factors are calculated according to the following equation:

$$GHG_{TtW} = \frac{\left(1 - C_{slip}\right) \times \left(C_{fCO_2} + C_{fCH_4} \times GWP_{CH_4} + C_{fN_2O} \times GWP_{N_2O}\right) + \left(C_{slip} \times GWP_{CH_4}\right) - e_{occs}}{LHV_{alt}} \tag{9}$$

where

C_{slip} is the coefficient accounting for fuel slip (% of fuel mass);
C_{fCO_2} is the CO_2 emission conversion factor (g CO_2/g fuel);
C_{fCH_4} is the CH_4 emission conversion factor (g CH_4/g fuel);
C_{fN_2O} is the N_2O emission conversion factor (g N_2O/g fuel);
GWP_{CH_4} is the Global Warming Potential of methane (g CO_{2e}/g CH_4);
GWP_{N_2O} is the Global Warming Potential of N_2O (g CO_{2e}/g N_2O);
e_{occs} is the emission savings from on-board CO_2 capture and geological storage (g CO_{2e}/MJ);
LHV_{alt} is the lower heating value of alternative fuel (MJ/g).

2.3. MAC Model under Carbon Pricing

To incentivize the adoption of GHG emission abatement measures, several carbon pricing mechanism proposals are under discussion [37]. The carbon pricing is a market-based instrument that sets a price on carbon dioxide (CO_2) or equivalent GHG emissions. When considering the potential impact of carbon prices, the MAC calculation formula can be modified to the following form:

$$MAC' = \frac{\Delta NCOST'}{\Delta CO_{2e}} \tag{10}$$

where $\Delta NCOST'$ represents the new annual net cost taking into account the cost changes caused by the carbon price and ΔCO_{2e} is still given by Equation (6).

The new annual net cost will be reduced due to the lower cost of the market-based mechanism achieved by implementing emission abatement measures, and therefore,

$$\Delta NCOST' = IC + OC - CS - MS \quad (11)$$

$$MS = \Delta CO_{2e} \times CP \quad (12)$$

where

MS is the annual carbon price savings achieved by implementing the abatement measure (USD/year);
CP is the carbon price determined in the market-based mechanism (USD/t CO_{2e}).

By combining Equations (1), (10), (11) and (12), it can be derived that

$$MAC' = \frac{\Delta NCOST}{\Delta CO_{2e}} = \frac{\Delta NCOST - MS}{\Delta CO_{2e}} = \frac{\Delta NCOST - \Delta CO_{2e} \times CP}{\Delta CO_{2e}} = MAC - CP \quad (13)$$

2.4. MACC Construction

After the MAC value and abatement amount of each measure are calculated, a MACC can be constructed. The MACC is typically represented in a two-dimensional coordinate system in the form of a histogram, with the MAC value is displayed on the Y-axis and the annual GHG abatement amount on the X-axis. The abatement measures are arranged in ascending order of MAC value from left to right on the Y-axis [11]. Based on the results of the MAC value, abatement measures are typically classified into negative MAC measures and positive MAC measures. The negative MAC measures are below the X-axis, indicating that these measures can achieve an emission reduction while saving costs; whereas the positive MAC measures are above the X-axis, signifying that these emission reduction measures may require a cost input.

2.5. Sensitivity Analysis

The calculation results of the MACC model are affected by factors such as input parameters and assumptions. A sensitivity analysis provides a way to describe how the model result responds to changes in the input data and assumptions [20]. This study focuses on two important parameters: fuel price and carbon price. Fuel prices are significantly affected by global political and economic factors, and their fluctuations are difficult to predict. Carbon price may be subject to uncertainty due to market-based mechanism implementations, abatement technology development, and other factors.

3. Case Study

3.1. Ship Types

The primary focus of this paper is to examine the cost-effectiveness of applying greenhouse gas emission reduction measures to specific vessels. Therefore, it is necessary to select representative ship types as the subjects of study. To this end, five ship types featuring high GHG emission contributions and strong demand in the new-building market are considered: bulk carriers (61–63K DWT), container ships (8000 TEU), product tankers (115K DWT), crude oil tankers (315–320K DWT), and Ro-Ro passenger ferries (3500 DWT). The basic technical parameters and information of the five ship types are shown in Table 2 [19].

Table 2. Basic technical parameters and information of the five ship types.

Ship Type	Classification	Main Engine Power (kW)	Design Speed (kn)	Fuel Consumption (t/year)	Newbuilding Cost (Million USD)
Bulk carrier	Handysize (61–63K DWT)	10,000	14.6	4900	34.5
Container ship	8000 TEU	68,000	25.0	264,000	98
Product tanker	LR2 (115K DWT)	13,000	14.8	5400	63
Crude oil tanker	VLCC (315–320K DWT)	26,000	15.5	145,000	117.5
Ro-Ro passenger ferry	3500 DWT	16,000	20.3	7900	110

3.2. Abatement Measures

In this study, 19 typical emission reduction measures are screened for the MACC analysis by reviewing scientific studies and consulting industrial experts. The investigated 19 abatement measures can be classified into four categories: (1) 7 technical measures, (2) 3 operational measures, (3) 3 renewable energy utilization measures, and (4) 6 alternative fuels.

The majority of emission reduction measures are applicable to different ship types. However, several measures are influenced by factors such as ship type, tonnage, and main engine power, resulting in certain limitations on their applicability. To ensure a comprehensive assessment of the cost-effectiveness of different measures when applied to specific vessel types, the applicability of various measures is taken into consideration as extensively as possible. At the same time, some of these measures are considered to be mutually exclusive and are not suitable for simultaneous application, for instance, measures highly correlated in emission reduction mechanisms (such as Flettner rotor and rigid sail) or measures with incompatible applications (such as slow steaming and waste heat recovery).

Moreover, when considering applicable ship types for alternative fuels such as methanol and ammonia, the potential hazards and impacts of their toxicity on humans and the environment should be closely considered. Methanol has slight toxicity, and skin contact can cause irritation, inflammation, or burns. Methanol is not persistent in the environment and biodegrades quickly [38]. Methanol fuel has been practically applied on chemical tankers, Ro-Ro passenger ferries, and container ships, and the IMO guidelines for the safety of ships using methanol as fuel has been established. Therefore, the safety of methanol application on various ship types can be ensured. Ammonia is highly toxic, and contact can result in irritation, blindness, and even death [39,40]. Ammonia is also toxic to aquatic life and, because of its high solubility in water, can damage the marine ecology if large quantities are spilled. Current regulations do not permit the use of ammonia as a marine fuel due to its toxicity. The IMO is currently evaluating how the IGF Code needs to change to allow ammonia as fuel [41]. Accordingly, we consider that the applicable ship types for ammonia are mainly limited to cargo ships at the preliminary development stage.

Based on our literature review and expert consultation, basic information on ship type applicability, abatement potentials, investment costs, and operational costs of various energy efficiency measures and alternative fuels are collected and calculated, as detailed in Tables 3 and 4, respectively.

Table 3. Basic information for energy efficiency measures.

Category	Sub-Category	Abatement Measures	Applicability	Abatement Potential	Investment Cost (USD)	Operational Cost (USD)	Ref.
Energy efficiency measures	Operational measures	Slow steaming (SS, with 10% reduction)	All ship types except for cruise vessels and ferries	19%	N/A	N/A	[42]
		Optimization of Trim and Ballast (OTB)	All ship types	1.5–4%	26,700	N/A	[14]
		Propeller maintenance	All ship types	1%	3000–4500 (Maintenance at intervals of 5 years)	N/A	[17]
	Technical measures	Optimized water flow of hull openings (OWF)	All ship types	3%	42,000–240,000	N/A	[14,42]
		Air lubrication (AL)	• Bulk carriers and crude oil tanker > 60,000 dwt. • Container ships > 2000 TEU • LPG/LNG carriers	5–7%	Approx. 3% of shipbuilding cost	11,000	[14,42]
		Hull coating (HC)	All ship types	1.5%	Approx. 30 × DWT^(2/3) (Generally recoated at intervals of 5 years)	N/A	[42]

Table 3. *Cont.*

Category	Sub-Category	Abatement Measures	Applicability	Abatement Potential	Investment Cost (USD)	Operational Cost (USD)	Ref.
Energy efficiency measures	Technical measures	Propeller boss cap with fins (PBCF)	All ship types	2%	79,000–520,000	N/A	[14]
		Main engine tuning (MET)	All ship types	0.45%	27,000–48,000	N/A	[14,42]
		Waste heat recovery (WHR)	Main engine power ≥ 10,000 kW (slow steaming vessel would not be able to use WHR)	3–8%	327 USD/kW (Proportional to main engine power)	10,000–30,000/year	[43]
		Speed control of pumps and fans (SCPF)	All ship types	0.5%	100–200 USD/kW (Auxiliary engine power)	N/A	[44]
	Renewable energy sources	Flettner rotors (FR)	Bulk carriers, crude oil tankers, chemical tankers, and product tankers (above 10,000 DWT)	8.5%	2,000,000–4,000,000	N/A	[17,45]
		Rigid sails (RS)	Bulk carriers, crude oil tankers, chemical tankers, and product tankers (above 10,000 DWT)	3–5%	300,000–600,000	N/A	[43,45]
		Solar panels (SP)	Ships have sufficient deck space available (tankers, vehicle carriers, and Ro-Ro vessels)	0.2%	3400 USD/kW (Power of SP generally calculated as 1% of the auxiliary engine power)	N/A	[14,17]

Table 4. Basic information for alternative fuels.

Category	Sub-Category	Abatement Measures	Applicability	Abatement Potential	Investment Cost (USD)	Operational Cost (USD)	Ref.
Alternative fuels	Fossil fuel	LNG	All ship types	13.9%	Approx. 15–20% higher than conventional vessels	Mainly fuel cost	[34]
	Biofuels	Bio-LNG	All ship types	77.7%	Approx. 15–20% higher than conventional vessels	Mainly fuel cost	[34]
		Bio-methanol	All ship types	85.0%	Approx. 14.4% higher than conventional vessels	Mainly fuel cost	[34]
		Hydrotreated vegetable oil (HVO)	All ship types	82.1%	Equivalent to conventional vessels	Mainly fuel cost	[34]
	Electrofuels	E-methanol	All ship types	95%	Approx. 14.4% higher than conventional vessels	Mainly fuel cost	[34,46]
		E-ammonia	Cargo ships	100%	Approx. 21.2% higher than conventional vessels	Mainly fuel cost	[47]

3.3. Emission Factors

For alternative fuels with mature production technologies and emission factors well proven in the industry, such as LSFO, LNG and bio-LNG, the emission factors are calculated using the Well-to-Wake methodology specified in the IMO LCA guidelines. For alternative fuels whose production technology has not yet matured and default emission factors have not been specified in relevant regulations, such as bio-methanol, e-methanol, and e-ammonia, the emission factors in the relevant research literature are referenced. According to the sustainability criteria applied to alternative fuels in the IMO LCA guidelines, the Well-to-Wake GHG emission reduction potentials of various alternative fuels are evaluated with LSFO as the reference; this principle is also adopted in this study. The GHG emission factors of various marine fuels from the perspective of Well-to-Tank, Tank-to-Wake, and Well-to-Wake are summarized in Table 5.

Based on the results of Well-to-Wake emission factors, methanol or ammonia that is produced using fossil energy could lead to increased GHG emissions in a lifecycle perspective. Therefore, the fossil-based methanol and ammonia do not comply with the sustainability criteria and will not considered in the MACC analysis.

Table 5. GHG emission factors for alternative fuels.

Fuel Category	Fuel Type	Engine Type	GHG Emission Factors (g CO_{2e}/MJ)			Abatement Potential
			GHG_{WtT}	GHG_{TtW}	GHG_{WtW}	
Fossil fuels	LSFO	Diesel	13.2	76.8	90	Baseline
	LNG	DF Diesel	18.5	59.0	77.5	13.9%
	Methanol	DF Diesel	31.3	71.6	100.4	−14.3%
	Ammonia	DF Diesel	121	0	121	−34.4%
Biofuels	Bio-LNG	DF Diesel	−38.9	59.0	20.1	77.7%
	Bio-methanol	DF Diesel	−58.1	71.6	11.0	85.0%
	HVO	Diesel	−20.7	71.9	51.2	41.3%
Electrofuels	E-Methanol	DF Diesel	−67.1	71.6	4.5	95.0%
	E-Ammonia	DF Diesel	0	0	0	100%

3.4. Fuel Prices

As described in Table 3, the operational costs for using alternative fuels in the MAC calculation mainly consider the annual fuel cost. Considering that the operational lifecycle of a vessel typically spans 25 years, the calculation of annual fuel costs should be based on the average fuel prices for the next 25 years. Accordingly, the average price of each alternative fuel is derived from the fuel price prediction spanning from 2025 to 2050, as presented in Table 6 [48,49].

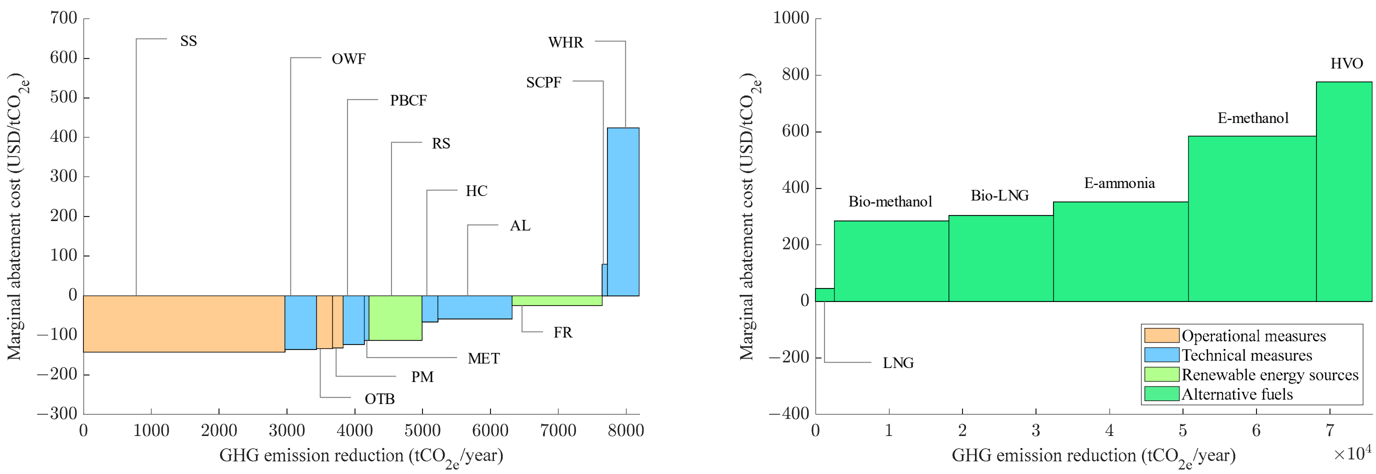
Table 6. Average price of alternative fuels (2025–2050).

Fuel Type	LSFO	LNG	Bio-LNG	Bio-Methanol	HVO	E-Methanol	E-Ammonia
Average price (USD/t)	455	425	1416	612	1750	1174	740

4. Results and Discussion

4.1. Results of MACC Basic Model

For bulk carriers (61–63K DWT), container ships (8000 TEU), product tankers (115K DWT), VLCCs (315–320K DWT), and Ro-Ro passenger ferries (3500 DWT), MACCs are developed for each vessel category over the period of 2025 to 2050, as shown in Figures 2–6. The MACC results for energy efficiency measures and alternative fuels are presented, respectively, in the left and right coordinate systems, as the emission reduction potential of the two category measures are evaluated based on the Tank-to-Wake and Well-to-Wake approaches, respectively.



(**a**) (**b**)

Figure 2. MACC results for bulk carriers (61–63K DWT). (**a**) Energy efficiency measures. (**b**) Alternative fuels.

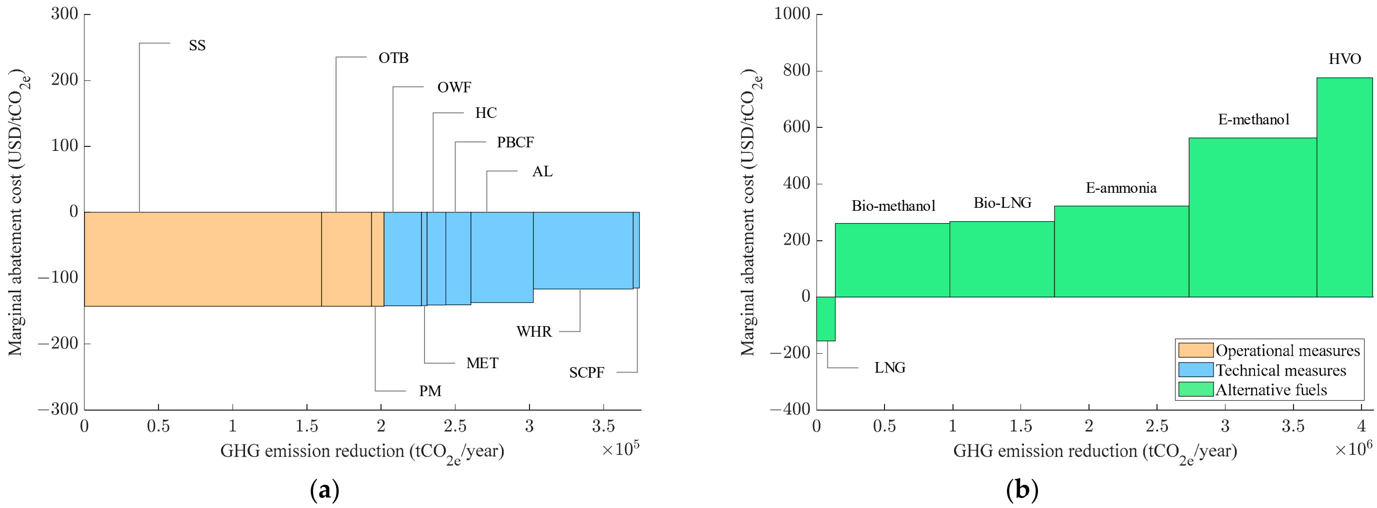


Figure 3. MACC results for container ships (8000 TEU). (**a**) Energy efficiency measures. (**b**) Alternative fuels.

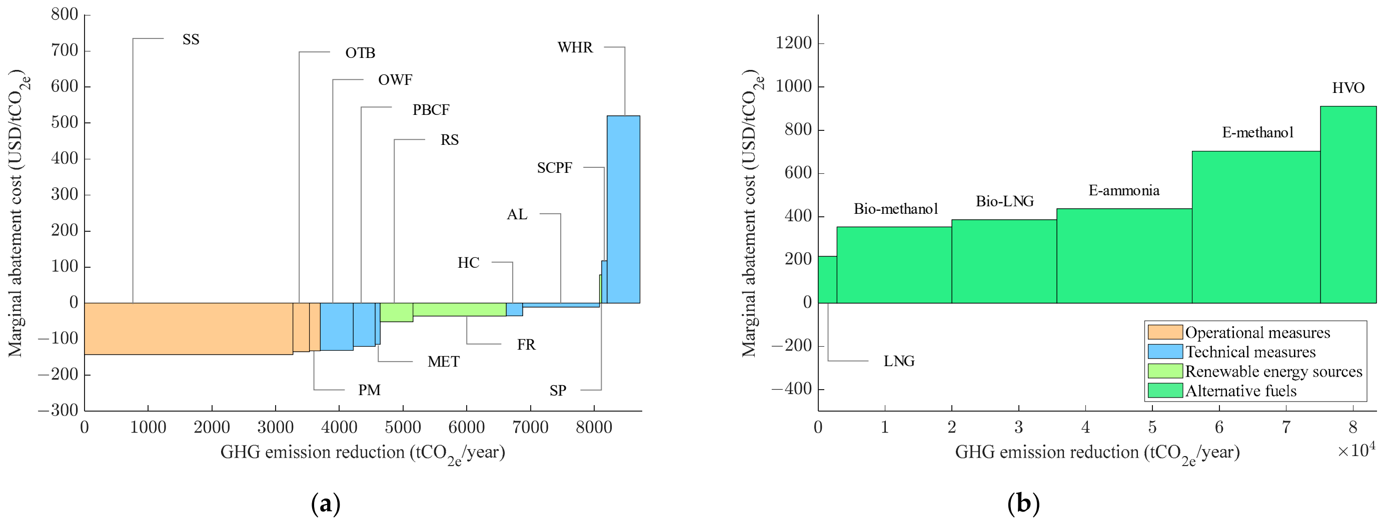


Figure 4. MACC results for product tank (115K DWT). (**a**) Energy efficiency measures. (**b**) Alternative fuels.

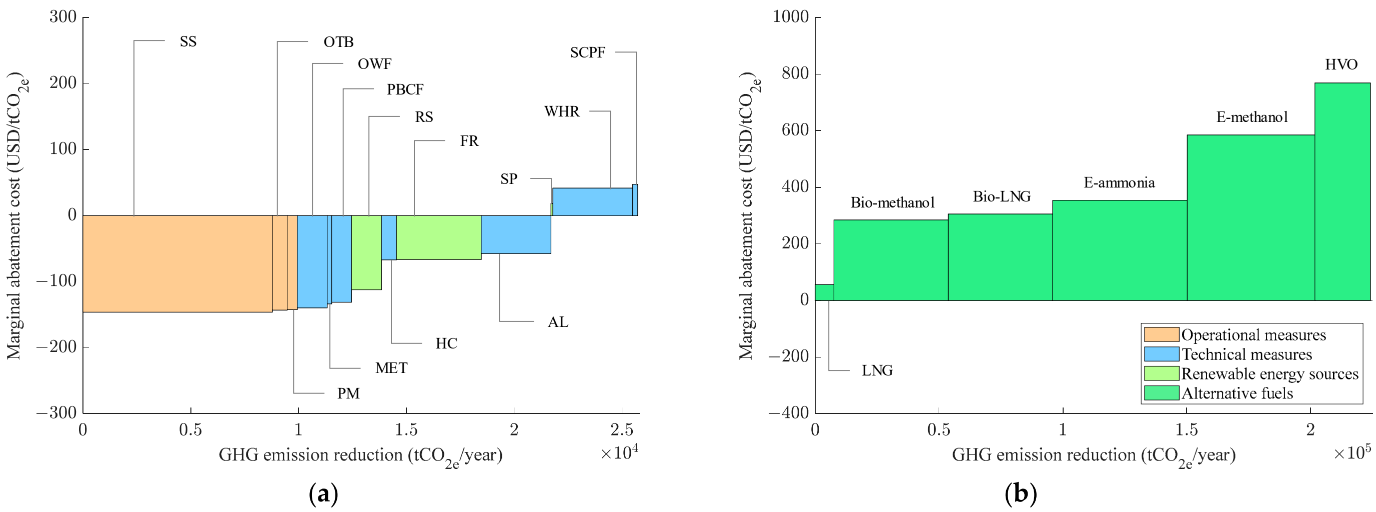


Figure 5. MACC results for VLCCs (315–320K DWT). (**a**) Energy efficiency measures. (**b**) Alternative fuels.

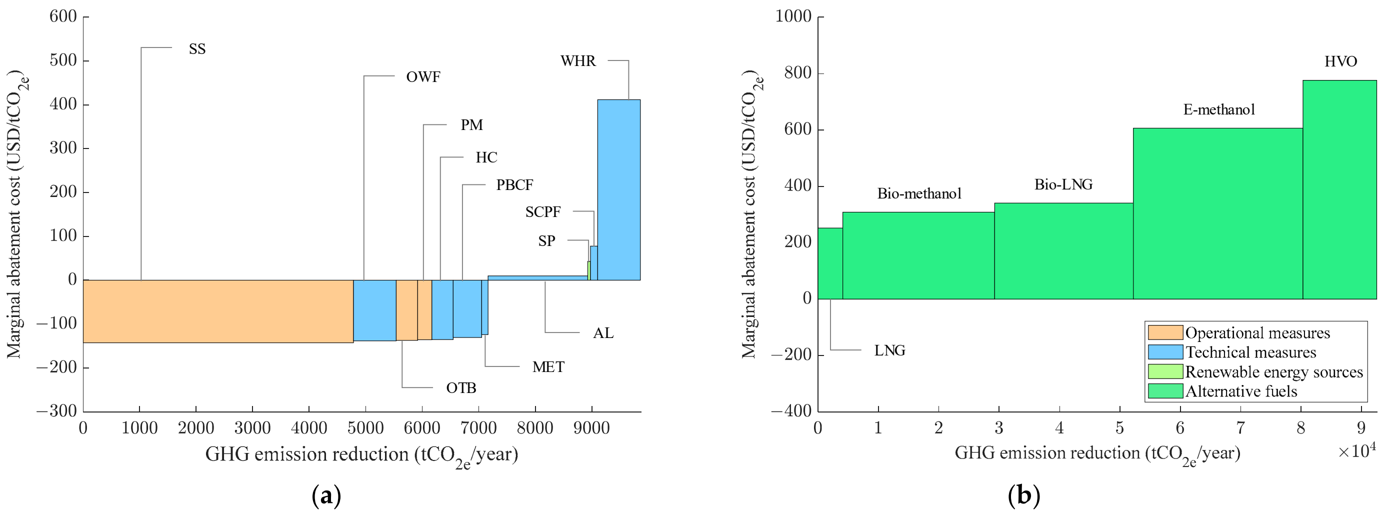


Figure 6. MACC results for Ro-Ro passenger ferries (3500 DWT). (**a**) Energy efficiency measures. (**b**) Alternative fuels.

Figures 2a, 3a, 4a, 5a and 6a show that, in terms of energy efficiency measures, the cost-effective performance of various energy efficiency measures generally follows the same order from the perspective of sub-category classification: operational measures, technical measures, and renewable energy utilization measures. Among the operational measures, slow steaming offers the most optimal cost-effectiveness and can achieve substantial emission reductions, while trim and ballast optimization, and propeller maintenance have relatively high cost-effectiveness but achieve lower emission reductions. Regarding the technical measures, the optimized water flow of hull openings, main engine tuning, hull coating, and propeller boss cap with fins are all cost-effective technologies when applied to the five ship types. Air lubrication is a cost-effective technology for the four cargo ships but becomes a cost-positive technology for the Ro-Ro passenger ferry. A waste heat recovery system and speed control of pumps and fans are cost-positive technologies for bulk carriers, product tankers, VLCCs, and Ro-Ro passenger ships and are a cost-effective technology when applied to container ships. Container ships have the highest fuel consumption, and thus, the investment involved in applying of a waste heat recovery system and speed control of pumps and fans can be recovered by saving fuel costs. As for renewable energy utilization measures, a rigid sail and Flettner rotors are both cost-effective technologies for applicable ship types, i.e., bulk carriers, product tankers, and VLCCs. A rigid sail presents better a cost-effective performance than Flettner rotors mainly due to its lower investment cost than the latter. A solar panel proved to be a cost-positive technology for applicable ship types, i.e., product tankers, VLCCs, and Ro-Ro passenger ferries, owing to its high investment cost and limited abatement potentials.

As can be seen from Figure 6a, the change pattern in the cost-effective performance of applying most energy efficiency measures for the Ro-Ro passenger ship is basically in line with the other four cargo ships, but there are still some differences in a few measures. Due to the high investment cost and relatively limited fuel consumption of the Ro-Ro passenger ship, it is more difficult to recover the investment by saving on fuel costs, so air lubrication is a cost-positive measure for Ro-Ro passenger ships. Furthermore, a rigid sail and Flettner rotors are not technically feasible measures for Ro-Ro passenger ships due to a lack of sufficient deck space for installation.

The results of the application of cost-effective energy efficiency measures are summarized in Table 7. Bulk carriers, container ships, product tankers, VLCCs, and Ro-Ro passenger ferries can achieve cumulative emission reductions of 40%, 36.5%, 38.5%, 38.5%, and 28.5%, respectively, cost-effectively. Accordingly, the resulting annual cost savings are USD 0.75 million, USD 43.34 million, USD 0.69 million, USD 2.18 million, and USD 1.0 million, respectively.

Table 7. Results of application of cost-effective energy efficiency measures.

Ship Type	Energy Efficiency Measures with Negative MAC Values		
	Ranking Orders	Abatement Potentials	Annual Cost Savings (million USD)
Bulk carrier (61–63K DWT)	SS, OWF, OTB, PM, PBCF, MET, RS, HC, AL	40%	0.75
Container ship (8000 TEU)	SS, OTB, PM, OWF, MET, HC, PBCF, AL, SCPF	36.5%	43.34
Product tanker (115K DWT)	SS, OTB, PM, OWF, PBCF, MET, RS, HC, AL	38.5%	0.69
VLCC (315–320K DWT)	SS, OTB, PM, OWF, MET, PBCF, RS, HC, AL	38.5%	21.8
Ro-Ro passenger ferry (3500 DWT)	SS, OWF, OTB, PM, HC, PBCF, MET	28.5%	1.0

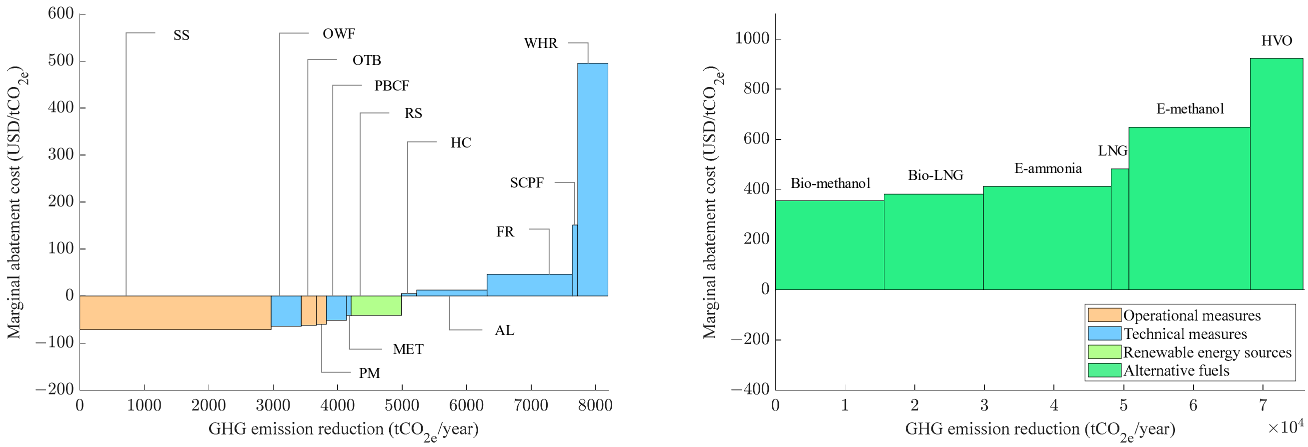
Figures 2b, 3b, 4b, 5b and 6b show that, in terms of alternative fuels, the cost-effectiveness ranking of various alternative fuels applied to the four cargo ship types remains consistent, namely LNG, bio-methanol, bio-LNG, e-ammonia, e-methanol, and HVO. Compared with the cargo ships, the passenger ships are more sensitive to the application of fuels with high toxicity hazards. Considering that ammonia is highly toxic and can cause serious injuries and fatalities to humans depending on the level of ammonia concentration exposed [50], the e-ammonia option is not considered in the Ro-Ro passenger ferry. Therefore, the ranking of alternative fuels for the Ro-Ro passenger ferry is LNG, bio-methanol, bio-LNG, e-methanol, and HVO. The LNG fuel shows the best cost-effective performance for the investigated five typical ship types, but its lifecycle emission reduction potential is relatively lower as it is still from fossil resources. The utilization of LNG fuel on container ships represents a cost-effective technology, leading to greenhouse gas emission reductions while realizing cost savings of approximately USD 150 per ton of $CO_{2e.}$ However, the application of LNG fuel to bulk carriers, product tankers, VLCCs, and Ro-Ro passenger ferries is a cost-positive technology. This is owing to the fact that applying LNG fuel involves a high investment cost, and it is difficult for ship types with limited fuel consumptions to counterbalance the investment by saving on fuel costs. Among the biofuels, bio-methanol performs slightly better than bio-LNG in cost-effective performance and lifecycle emission reduction potential. HVO presents the worst cost-effective performance among biofuels, owing to its lifecycle emission reduction potential being lower than that of bio-methanol and bio-LNG as well as its high fuel cost. For electrofuels, e-ammonia presents a better cost-effective performance than e-methanol. Although the lifecycle emission reductions of e-ammonia and e-methanol fuel are generally comparable, the cost of e-ammonia is significantly lower than that of e-methanol, thus making e-ammonia perform better in cost-effectiveness than e-methanol.

4.2. Sensitivity Analysis

The sensitivity analysis of bulk carriers (61–63K DWT) is presented in this section. The aim is to investigate the robustness of the cost-effective measures under the fluctuation scenarios of important input parameters such as fuel oil price and carbon price. For other vessel categories, the sensitivity analysis can be conducted following the same approach.

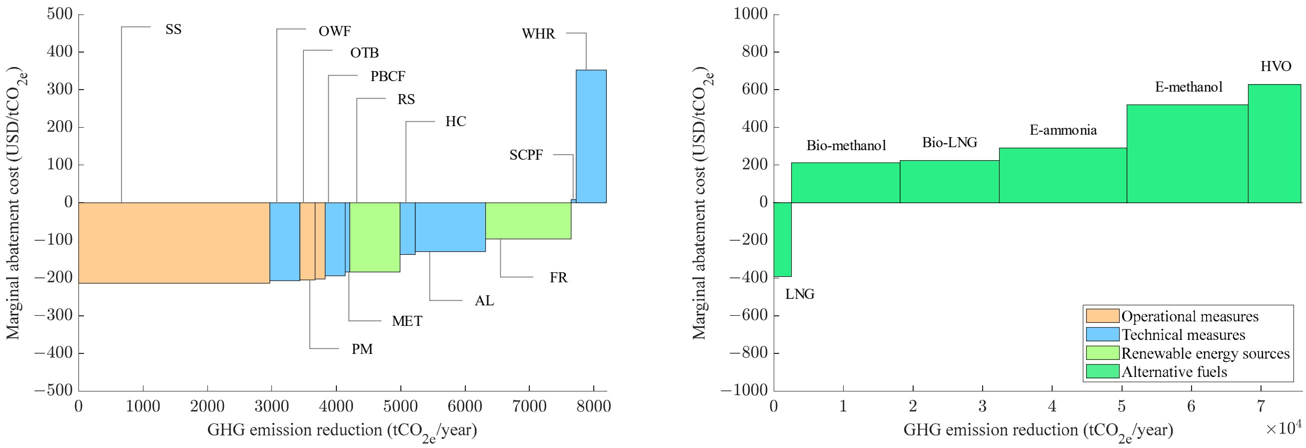
4.2.1. Fuel Oil Price

The MACC results of bulk carriers (61–63K DWT) for the changing average price of conventional fuel (LSFO) in the scenarios of a 50% decrease, a 50% increase, a 100% increase, and a 150% increase are illustrated in Figures 7–10. The changes in MAC value for various abatement measures under the sensitivity analysis on LSFO price carbon price are summarized in Table 8.



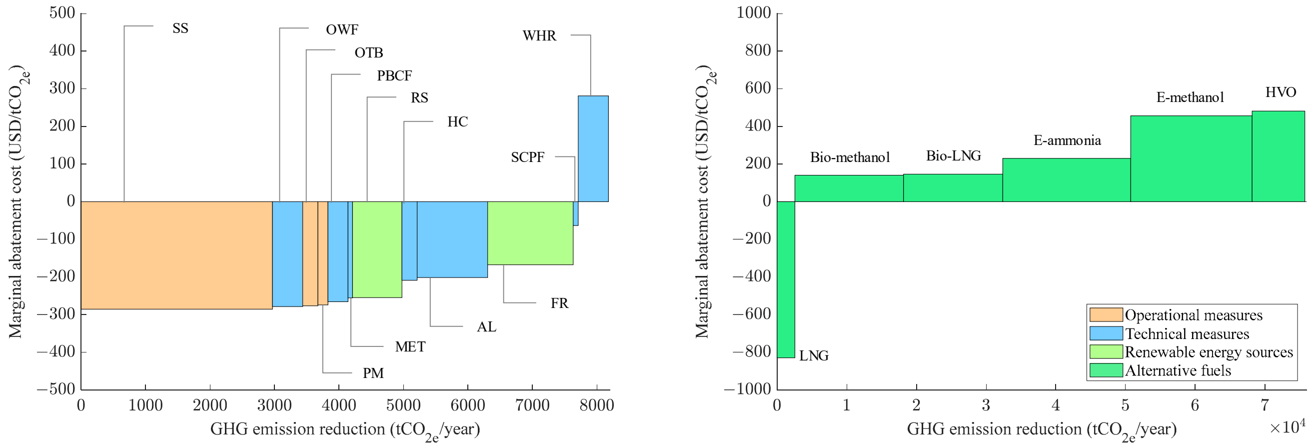
(**a**) (**b**)

Figure 7. MACC results for bulk carriers (LSFO price decrease 50%). (**a**) Energy efficiency measures. (**b**) Alternative fuels.



(**a**) (**b**)

Figure 8. MACC results for bulk carriers (LSFO price increase 50%). (**a**) Energy efficiency measures. (**b**) Alternative fuels.



(**a**) (**b**)

Figure 9. MACC results for bulk carriers (LSFO price increase 100%). (**a**) Energy efficiency measures. (**b**) Alternative fuels.

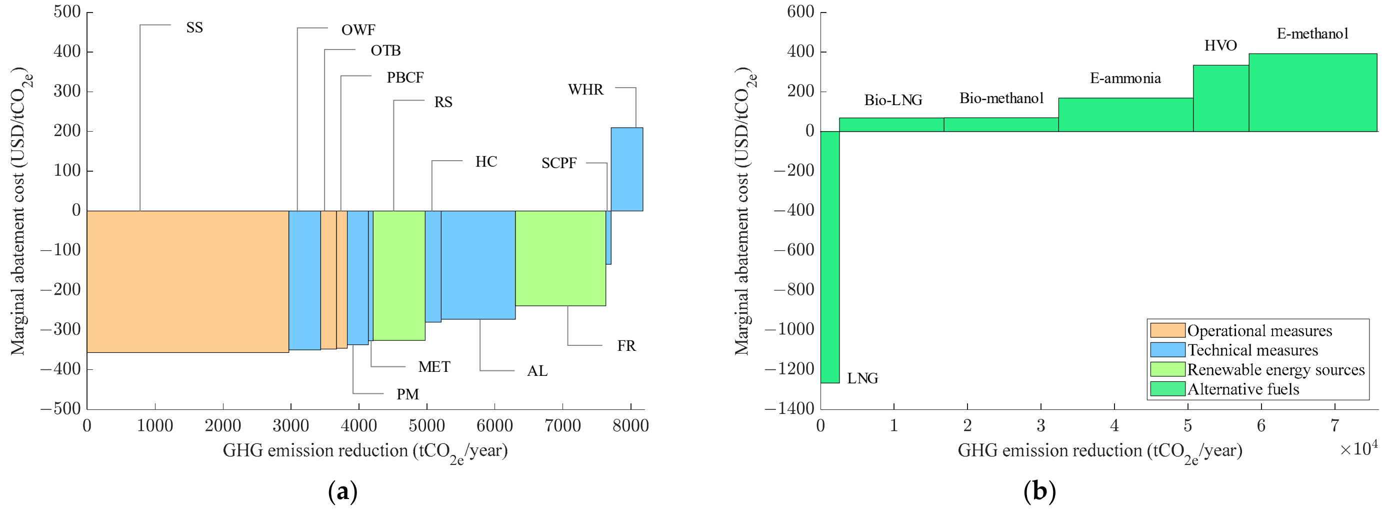


Figure 10. MACC results for bulk carriers (LSFO price increase 150%). (**a**) Energy efficiency measures. (**b**) Alternative fuels.

Table 8. Changes in MAC value for various abatement measures under sensitivity analysis on LSFO price.

Category	Ranking (Baseline)	Abatement Measures	LSFO Price (% Change from Baseline)				
			−50%	Baseline (455 USD/t)	+50%	+100%	+150%
			MAC (USD/tCO_{2e})				
Energy efficiency measures	1	Slow steaming	−71	−143	−214	−285	−357
	2	Optimized water flow of hull openings	−64	−136	−207	−278	−350
	3	Optimization of Trim and Ballast	−62	−134	−205	−277	−348
	4	Propeller maintenance	−60	−131	−203	−274	−346
	5	Propeller boss cap with fins	−52	−123	−194	−266	−337
	6	Main engine tuning	−42	−113	−184	−256	−327
	7	Rigid sails	−41	−112	−183	−255	−326
	8	Hull coating	5	−66	−137	−209	−280
	9	Air lubrication	13	−59	−130	−201	−273
	10	Flettner rotors	46	−25	−96	−167	−239
	11	Speed control of pumps and fans	151	80	8	−63	−134
	12	Waste heat recovery	495	424	353	281	210
Alternative fuels	1	LNG	482	45	−392	−829	−1266
	2	Bio-methanol	355	284	212	141	68
	3	Bio-LNG	382	303	225	147	69
	4	E-ammonia	412	352	291	230	169
	5	E-methanol	648	584	520	456	334
	6	HVO	922	776	629	482	392

In the LSFO price decrease 50% scenario, the emission reduction potential from the application of cost-effective measures decreases from 40% to 32% compared with the baseline MACC. All of the energy efficiency measures experience a decrease in cost-effectiveness, while their ranking remains the same as the baseline scenario. Furthermore, hull coating, air lubrication, and Flettner rotors transform from cost-effective measures to cost-positive measures. For alternative fuels, the cost-effectiveness of all alternative fuels present a significant decrease, and the order of cost-effectiveness is as follows: bio-methanol, bio-LNG, e-ammonia, LNG, e-methanol, and HVO. The cost-effective performance of LNG fuel shows the most significant decrease, with its ranking dropping from the first to the fourth. This can be attributed to the fact that a 50% decrease in LSFO price leads to the LNG price becoming higher than the LSFO price. Consequently, using LNG fuel does not lead to fuel cost savings; instead, it results in a fuel cost increase.

In the LSFO price increase 50% scenario, the emission reduction potential from the application of cost-effective measures can reach 40%, remaining the same as the baseline MACC. The reason is that although improvements in cost-effectiveness for all the energy efficiency measures can be achieved, the speed control of pumps and fans as well as the waste heat recovery system still remain measures with positive costs, indicating that the cost-effective measures are the same as those in the baseline scenario. In terms of alternative fuels, the LNG fuel transforms from a cost-positive measure to a cost-effective measure compared with the baseline MACC results. Although LNG-powered vessels have high initial investment costs, a 50% increase in fuel prices would notably increase the price gap between LSFO and LNG, thereby effectively compensating for the higher investment costs through fuel cost savings and thus obtaining a negative MAC value. Bio-methanol, bio-LNG, e-ammonia, e-methanol, and HVO persist as cost-positive measures, but they all obtain improvements in cost-effectiveness.

In the LSFO price increase 100% scenario, the emission reduction potential from the application of cost-effective measures increases from 40% to 41% compared with the baseline MACC. This can be attributed to the fact that the speed control of pumps and fans transforms from a cost-positive measure to a cost-effective measure, thus making a contribution to the 1% increase in the emission reduction potential. The ranking order of all the energy efficiency measures remains the same as that for the baseline MACC scenario. In terms of alternative fuels, LNG, bio-methanol, bio-LNG, e-ammonia, e-methanol, and HVO persist as cost-positive measures, with the same ranking order as the baseline, but they all obtain improvements in cost-effectiveness.

In the LSFO price increase 150% scenario, the emission reduction potential from the application of cost-effective measures remains at 41% compared with the 100% price increase scenario. The reason is that the waste heat recovery system still remains a measure with a positive cost, and thus, the cost-effective measures and the associated emission reduction amount is the same as the 100% price increase scenario. In terms of alternative fuels, the ranking of cost-effective performance changed compared with that of the baseline scenario. Specifically, the cost-effective performance of bio-LNG surpasses that of bio-methanol, and the cost-effectiveness of HVO becomes superior to that of e-methanol. The 150% increase of LSFO price further narrow the price gaps between alternative fuels and LSFO, thereby decreasing the fuel costs for different fuel options. Consequently, the net costs and the corresponding cost-effectiveness ranking of different fuel schemes changed accordingly.

4.2.2. Carbon Price

In Figure 11, reference lines for the carbon prices of three scenarios (USD 100, 200, and 300 per ton of CO_{2e}) are illustrated based on the MACC baseline for bulk carriers (61–63K DWT). The changes in MAC value for various abatement measures under the sensitivity analysis on carbon price are summarized in Table 9. The comparison between the MACC value and the reference lines allows for an analysis of the impact of different carbon prices on the MACC.

For energy efficiency measures, in the scenario without a carbon pricing mechanism, the speed control of pumps and fans as well as the waste heat recovery are abatement measures with positive MACs. In the scenario of implementing a carbon price of USD 100 per ton of CO_{2e}, the MAC value of the speed control of pumps and fans becomes negative, while waste heat recovery still remains positive. In the scenario of a carbon price of USD 200 per ton of CO_{2e}, all of the measures can gain further improvements in cost-effectiveness. Due to the high investment costs of waste heat recovery systems, even implementing a carbon price of USD 300 per ton of CO_{2e} still cannot render them cost-effective measures. In general, the majority of energy efficiency measures are inherently cost-effective, and thus, shipping companies have a motivation to voluntarily apply these measures for economic considerations. Therefore, the application and promotion of cost-effective energy efficiency measures are not decisively influenced by the implementation of a carbon price.

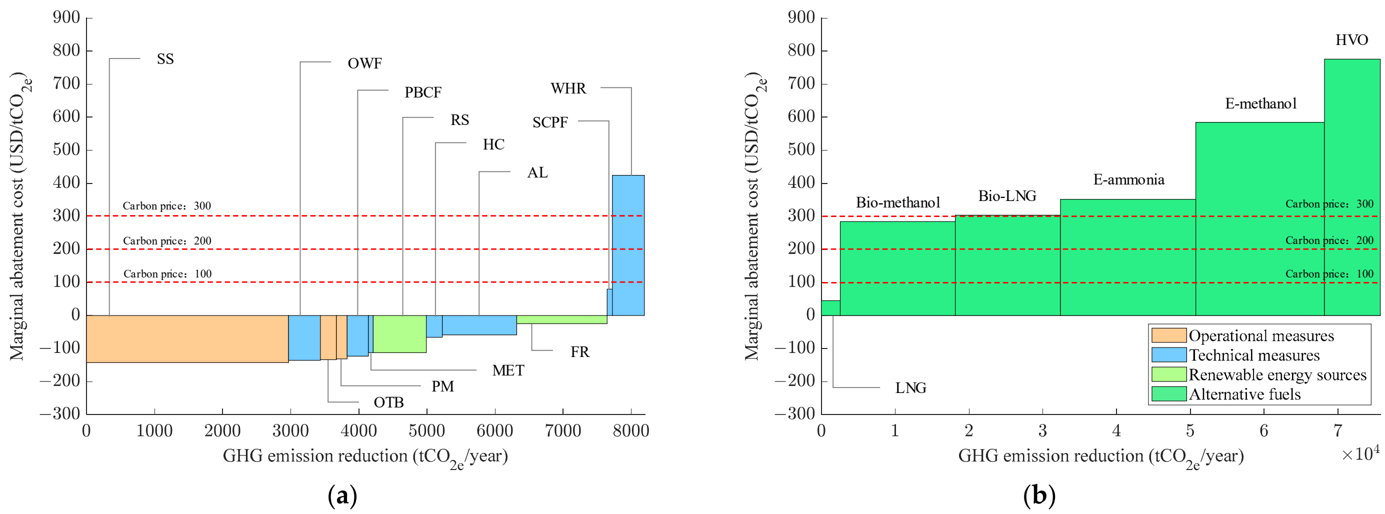


Figure 11. Impact of carbon price on MACC results (61–63K DWT bulk carrier). (**a**) Energy efficiency measures. (**b**) Alternative fuels.

Table 9. Changes in MAC value for various abatement measures under sensitivity analysis on carbon price.

Category	Ranking (Baseline)	Abatement Measures	Carbon Price (USD/t CO_{2e})			
			Baseline	100	200	300
			MAC (USD/tCO_{2e})			
Energy efficiency measures	1	Slow steaming	−143	−243	−343	−443
	2	Optimized water flow of hull openings	−136	−236	−336	−436
	3	Optimization of Trim and Ballast	−134	−234	−334	−434
	4	Propeller maintenance	−131	−231	−331	−431
	5	Propeller boss cap with fins	−123	−223	−323	−423
	6	Main engine tuning	−113	−213	−313	−413
	7	Rigid sails	−112	−212	−312	−412
	8	Hull coating	−66	−166	−266	−366
	9	Air lubrication	−59	−159	−259	−359
	10	Flettner rotors	−25	−125	−225	−325
	11	Speed control of pumps and fans	80	−20	−120	−220
	12	Waste heat recovery	424	324	224	124
Alternative fuels	1	LNG	45	−55	−155	−255
	2	Bio-methanol	284	174	74	−26
	3	Bio-LNG	303	203	103	3
	4	E-ammonia	352	252	152	52
	5	E-methanol	584	484	384	284
	6	HVO	776	676	576	476

In terms of alternative fuels, without the application of a carbon pricing mechanism, all fuel options are abatement measures with positive MACs. In the scenario of a carbon price of USD 100 per ton of CO_{2e}, the MAC value of LNG fuel becomes negative, while the MAC of other fuel options still remains positive. When implementing a carbon price of USD 300 per ton of CO_{2e}, bio-methanol turns into a cost-effective measure, although the margin is relatively small. Biomass LNG is positioned at the threshold between a cost-positive measure and a cost-effective one. For e-methanol, e-ammonia, and HVO, it can be observed that a carbon price of USD 400 to 800 per ton of CO_{2e} is required to turn it into a cost-effective measure. Generally, as alternative fuels commonly have high costs, a carbon price of USD 300–800 per ton of CO_{2e} is required to offset the cost gap with conventional fuel-powered vessels, making the use of alternative fuels economically feasible. However, taking the EU carbon market as an example, the average carbon price in 2023 is approximately USD 100 per ton of CO_2. This carbon price level may have some contribution in promoting the use of LNG fuel, yet it is still far from sufficient to stimulate the industry's scaled investment and application of alternative fuels such as biofuels and electrofuels.

5. Conclusions

In this study, the investigation of the economic performance of energy efficiency measures and alternative fuels for shipping GHG emission reduction was carried out using a cost-effectiveness model based on the MACC methodology. By innovatively introducing the Tank-to-Wake and Well-to-Wake emission assessment approaches into the MACC methodology, the model was capable of reflecting distinguished GHG emission abatement potentials for energy efficiency measures and alternative fuels from the down-stream and lifecycle basis, respectively. Representative ship types with significant GHG emission contributions, including bulk carriers (61–63K DWT), container ships (8000 TEU), product tankers (115K DWT), VLCCs (315–320K DWT), and Ro-Ro passenger ships (3500 DWT), were taken as research cases. MACCs were developed for each vessel type for various GHG abatement measures including operational measures, technical measures, renewable energy sources, and alternative fuels. The main conclusions derived from this work are summarized as follows:

- The energy efficiency measures that are cost-effective when applied to the five investigated ship types mainly include slow steaming, trim and ballast optimization, propeller maintenance, optimized water flow of hull openings, main engine tuning, hull coating, and propeller boss cap with fins. Ship owners can prioritize the adoption of these energy efficiency measures in their decarbonization strategies.
- The cost-effectiveness ranking of various alternative fuels applied to the typical ship types generally remains consistent, namely LNG, bio-methanol, bio-LNG, e-ammonia, e-methanol, and HVO.
- The cost-effective performance of LNG fuel is closely related to the application ship types and its fuel consumption. LNG fuel is a cost-effective option when applied to 8000 TEU container ships with an annual fuel consumption of 264,000 t. However, it becomes a measure with a positive MAC value for the other four investigated ship types with relatively lower fuel consumption.
- The adoption of alternative fuels including bio-methanol, bio-LNG, e-ammonia, e-methanol, and HVO on the investigated five typical ship types are proven to be measures with positive MAC values due to their high fuel costs.
- The cost-effective performance of energy efficiency measures will be influenced to varying degrees in different LSFO price scenarios, but the cost-effectiveness ranking of the various energy efficiency measures remains consistent.
- Fluctuations in fuel oil price significantly affect the cost-effective performance of different alternative fuels. Moreover, when fuel prices increase or decrease to a certain extent, the ranking of the cost-effective performance of different alternative fuels will change accordingly.
- A carbon pricing mechanism does not have a significant effect on most energy efficiency measures, but it has a certain stimulating effect on several cost-positive energy efficiency measures, such as waste heat recovery system, speed control of pumps and fans, and solar panels.
- A carbon pricing mechanism can effectively improve the cost-effective performance of alternative fuels with a high fuel cost. To bridge the fuel cost gap between the conventional fuels and alternative fuels such as bio-methanol, bio-LNG, e-ammonia, e-methanol, and HVO, a carbon price ranging from USD 300 to 800 per ton of CO_{2e} needs to be imposed.

This study developed a framework for evaluating the cost-effective performance of marine alternative fuels and energy efficiency measures. It can be used as a supporting tool for shipping companies to develop and optimize decarbonization strategies and for maritime authorities to plan and formulate market-based mechanisms on carbon pricing. A potential future research direction is to introduce more emerging and gradually matured abatement measures, such as an on-board carbon capture system and carbon-neutral fuels with novel production processes, into the evaluation framework so as to give a more comprehensive evaluation. In addition, it would be interesting to investigate the contribution of various cost-effective measures to the Energy Efficiency Existing Ship Index (EEXI) and Carbon Intensity Indicator (CII).

Author Contributions: Conceptualization, H.T. and Y.Z.; methodology, H.T.; software, H.T. and Z.L.; validation, Z.L. and Y.Z.; formal analysis, H.T. and Z.L.; investigation, H.T. and Y.Z.; resources, H.T., Z.L. and Y.Z.; data curation, H.T. and Y.Z.; writing—original draft preparation, H.T.; writing—review and editing, H.T., Z.L. and Y.Z.; visualization, H.T. and Z.L.; supervision, Y.Z.; project administration, H.T. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: The data that support the findings of this study are available within the article.

Acknowledgments: We thank the anonymous reviewers whose comments helped improve and clarify this manuscript.

Conflicts of Interest: The authors declare no conflicts of interest.

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