

REVIEW

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A review on carbon emissions of global shipping

Shiyu Deng¹ and Zhifu Mi^{1*}

Abstract

Carbon dioxide (CO₂) emissions from shipping account for about 3% of total annual anthropogenic CO₂ emissions and are assumed to increase markedly without mitigation measures. Following the introduction of the net-zero emissions target, the large uncertainties and challenges of a low-carbon transition in the shipping industry have raised concerns in the scientific community. This study presents a compressive review of CO₂ emission inventories for the shipping industry, examines the historical CO₂ emission trends and associated estimation uncertainties due to different methodologies, and further discusses the CO₂ reduction measures and potential published in the literature. We aim to answer what has happened and what will happen in the shipping industry to identify potential challenges in realizing a roadmap to net-zero emissions. Here we show that there is a 20% variation in CO₂ emissions reported by the reviewed inventories due to differences in estimation methodology and study scope, with top-down approaches (e.g., IEA) advancing the timeliness of emission estimation and bottom-up approaches (e.g., CAMS-GLOB-SHIP and EDGAR) facilitating the availability of geospatial information. The rebound in CO₂ emissions by 2021 underscores the urgency of decoupling growth in seaborne trade from carbon emissions, and source and process control measures will provide most of the abatement potential, leaving the remaining abatement burden to be borne by carbon capture and out-of-industry transfers by 2050. However, secondary emissions, navigational safety, crew welfare, international cooperation, and economic and technical feasibility pose challenges to current low-carbon development. There remains a long way to go towards realizing the goal of the net-zero target, it requires the coordination and cooperation of all operators along the entire value chain of the shipping industry.

Keywords Shipping emissions, Carbon dioxide, Abatement measures, Net-zero target

1 Introduction

Driven by a surge in commercial demand, seaborne trade has seen a remarkable development to deliver more than 80% of global merchandise in 2019. Accordingly, the loaded volume of international maritime trade has witnessed 10 years of constant growth until the COVID-19 pandemic happened, rising from 7,857 million tons (Mt) in 2009 to 11,005 Mt in 2018 (UNCTAD, 2020). This predominance is particularly pronounced in developing

economics (UNCTAD, 2020). In 2020, international seaborne trade reduced by nearly 4% due to the COVID-19 pandemic but rebounded in 2021 as the global economy began to recover (UNCTAD, 2022).

In return for remarkable volume growths, the environmental impacts of intensive maritime transportation came to be emphasized, especially the climate impacts from exhaust Greenhouse Gases (GHG) (IMO, 2021; Ytreberg et al., 2021). Despite being one of the most efficient freight options, maritime transportation also emitted 1,076 Mt of GHG emissions in 2018, of which 1,056 Mt were CO₂ emissions, accounting for around 3% of total anthropogenic CO₂ emissions. However, the rate is assumed to rise to 17% by 2050, indicating global shipping CO₂ emissions are heading in

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the wrong direction unless actions are taken (ISEMAR, 2020). This is due to the shipping industry being more heavily fossilized than other industries, as oil contributed more than 99% of total energy demands historically (IEA, 2023). Without energy transformation, the shipping industry will be less energy efficient along with the age of fleets (UNCTAD, 2022). On the other hand, international maritime industries involve cross-regional trade and cost transference, which makes it difficult to attribute the abatement responsibilities for different stakeholders (Daioglou et al., 2020; Wang et al., 2021). The shipping industry emerged to be a hindrance for the Paris Agreement to limit global warming under 1.5 Celsius degrees.

Motivated by the global green revolution wave, the shipping industry is also actively seeking low-carbon transformation. In early 2003, the International Maritime Organization (IMO) adopted Assembly Resolution A.963(23) on GHG Reductions from Ships, which for the first time formally introduced greenhouse gas emission controls, urging the Marine Environment Protection Committee (MEPC) to undertake a series of assessments and development work. In 2011, MEPC adopted resolution MEPC.203(62) on inclusion of regulations on energy efficiency for ships in MARPOL Annex VI, introducing mandatory technical (Energy Efficiency Design Index, EEDI), operational (Ship Energy Efficiency Management Plan, SEEMP) measures, and energy efficiency technical cooperation and transfer measures for freight energy efficiency. In 2018, MEPC.304(72) added the Initial Strategy to enhance CO₂ abatement ambitions and proposed to “in 2030, reduce CO₂ emission intensity by about 40% compared to 2008; in 2050, reduce CO₂ emission intensity by about 70% and total emissions by 50%; and achieve zero carbon emissions within this century consistent with the Paris Agreement temperature goals”. In line with this goal, two new regulatory measures from the IMO, Energy Efficiency Existing Ship Index (EEXI) and carbon intensity indicator (CII), came into force from 1st January 2023 to improve energy efficiency. Recently, the adoption of the 2050 Agenda for shipping net-zero GHG emissions on the 2023 IMO GHG Strategy (MEPC 80) has renewed international efforts to pursue and accurately measure global actions towards low-carbon shipping industry. The revised 2023 GHG Strategy advanced net-zero GHG emissions from international shipping to 2050 and encourage the uptake of alternative zero and near-zero GHG technologies, fuels and/or energy sources to represent at least 5%, striving for 10% of the energy used by international shipping by 2030. In addition, the MEPC adopted the Guidelines on life cycle GHG intensity of marine fuels to standardize the calculation approaches, allowing for a Well-to-Wake calculation

of total GHG emissions related to the production and use of marine fuels.

Regionally, many countries or regions have also been taking actions to reduce GHG emissions from the shipping industry. China has fully implemented short-term measures to reduce GHG emissions from ships and continues to lead in designing and building ammonia-ready vessels. The European Union (EU) has brought the shipping industry under the control of the EU Carbon Emissions Trading System (EU ETS), starting with vessels above 5,000 gross tonnages. In the United States, the Inflation Reduction Act (IRA) enacted in 2022 not only includes direct support for reducing port emissions through electrification, but also significantly contribute to greening the ammonia supply chain through its clean hydrogen tax incentive (IEA, 2023). All these milestone measures indicate that carbon reduction in international shipping is on a fast track.

In order to gain insight into the low-carbon solutions of the shipping industry, studies were carried out to characterize emissions from shipping. For instance, Jalakanen et al. (2009, 2016) calculated fuel consumption and emissions for the European sea areas and Baltic Sea area; Russo et al. (2018) and Zhang et al. (2017) compared methodologies and spatial/temporal resolution of ship emission inventories over Europe and China; Eide et al. (2011) and Liu et al. (2018) made emission projections and cost–benefit analysis for future scenarios; Merk (2014) analyzed emissions in terms of ship type, mode of operation, seasonality, flag states, and energy efficiency; Bouman et al. (2017) evaluated and identified strategies to improve the eco-efficiency of port and ship activities; and Xing et al. (2020) reviewed existing emission reduction measures. All the above research topics are crucial for reducing CO₂ emissions from shipping. As the urgency of achieving the 2050 net-zero emissions agenda is becoming more and more apparent, the huge uncertainties and challenges of low-carbon transition in the shipping industry need to be discussed further.

The aims of this work are to comprehensively review and summarize studies reporting on relevant aspects of shipping emissions and challenges of achieving net zero in the shipping industry. In Section 2, we begin by reviewing ship CO₂ emissions inventories to identify historical technical, policy and economic changes to inform future shipping decarbonization. However, even if the trends in CO₂ emissions in the emission databases are consistent, their absolute amounts vary considerably (IMO, 2021). Thus, we reviewed the data sources and methods of representative inventories in Section 3 to make suggestions for standardizing emission calculation. In addition, based on previous research on emission reduction solutions, we deepen this discussion of the challenges and barriers to

widespread adoption of different decarbonization measures in Section 4. Finally, we assess the shortcomings of existing research in terms of what has been overlooked and what has not been clearly clarified in the low-carbon revolution of the shipping industry in Section 5.

2 Shipping emission inventories

For monitoring and guiding the progress of decarbonization, adequate and detailed emission inventories with geospatial information are necessary. Several studies have estimated the total amount and geospatial information of the ship-sourced CO₂ emissions. The IPCC AR6 report collected shipping emission datasets with long time series therein, including IMO GHG studies (IMO, 2009, 2015b, 2021), CEDS (Hoesly et al., 2018; O'Rourke et al., 2021), CAMS-GLOB-SHIP (Johansson et al., 2017; Granier et al., 2019), EDGAR (Janssens-Maenhout et al., 2019), etc. In addition, the International Energy Agency (IEA) also provides CO₂ emissions from international shipping industry based on energy consumption statistics (IEA, 2023).

Each emission inventory presents its own advantages and disadvantages (Table 1). One of the most authorized emission inventories is the IMO GHG studies, which provides robust emission estimations for different ship types/engines from 1990 to 2018 but lacks geospatial information. Based on timely availability of energy data, the IEA provides the latest insight into the rebound in shipping CO₂ emissions in the wake of the COVID-19 pandemic. In comparison, the CEDS database optimizes regional emission information, scaling shipping emissions to national levels over a much longer time series. CEDS v2021 produces consistent annual estimates of Black Carbon (BC), Carbon Monoxide (CO), CO₂, Ammonia (NH₃), Non-Methane Volatile Organic Compounds (NMVOC), Nitrogen Oxides (NO_x), Organic Carbon (OC), Sulfur Dioxide (SO₂) over the industrial era (1750–2021) along with Methane (CH₄) and Nitrous Oxide (N₂O) over recent decades.

With the adoption of AIS data, the CAMS-GLOB-SHIP dataset improves spatial resolution at the expense of timing length. CAMS-GLOB-SHIP v3.1 provides daily gridded (0.25° × 0.25°) shipping emissions from 2000 to 2018 for EC, CO, CO₂, NO_x, SO_x, VOC, OC, SO₄ and Ash. EDGAR v7 database provides gridded estimates of annual emissions at highest resolution (0.1° × 0.1°), but covers only three main greenhouse gases (CO₂, CH₄, N₂O) and fluorinated gases for the period 1970 to 2021.

Shipping CO₂ emissions witnessed three fluctuations in 2008, 2012 and 2019 respectively (Fig. 1). The emission increases in 2000–2008 were tightly coupled to growth in seaborne trade. After the financial crisis in 2008, the sharp upsurge in carbon dioxide emissions ceased and showed a slight decline. It has been seen as a period of rapid carbon intensity reduction by imposing EEDI measure that enabled decoupling of emissions from growth in transport demand (IMO, 2021). In addition, literature pointed out slow steaming led to 11% decrease in CO₂ emissions from containerships without the adoption of any new technology (Cariou, 2011). From 2014 to 2018, despite improvements in carbon intensity, the growth in demand dominated CO₂ emission rising (UNCTAD, 2020; IMO, 2021). Then, the restrictive regulations during the COVID-19 pandemic disrupted the shipping trade chain, reducing shipping CO₂ emissions in 2020 by approximately 10%. In line with rebounded seaborne trade, CO₂ emissions from the shipping industry grew by 5% in 2021 and are now back to 2017–2018 levels (IEA, 2023). The fastest growth, driven by global gas demand was for liquefied gas carriers followed by containerships and bulk carriers (UNCTAD, 2022). Indeed, the post-pandemic rebound trend warns of the need for further improvements in energy efficiency to offset the emissions-enhancing effects of increased demand, as emphasized in the requirements of Energy Efficiency Existing Ship Index (EEXI) and carbon intensity indicator (CII) regulations.

Table 1 Emission inventories for global shipping GHG emissions

Inventory	Time-length	Resolution	Including non-CO ₂ gases	Method
IMO ^a	1990–2018	Global	CH ₄ , N ₂ O, NO _x , VOC, PM _{2.5}	Bottom-up & Top-down
IEA ^b	2000–2022	Global	No	Top-down
CEDS v_2021	1750–2019	National	BC, CO, NH ₃ , NMVOC, NO _x , OC, SO ₂ , CH ₄ , N ₂ O	Top-down
CAMS-GLOB-SHIP v3.1	2000–2018	0.25° × 0.25°	NO _x , SO _x , CO, VOC, EC, OC, Ash, SO ₄	Bottom-up
EDGAR v7	1970–2021	0.1° × 0.1°	CH ₄ , N ₂ O, F-gases	Bottom-up & Top-down

^a The IMO inventory includes shipping emission data from the 2nd, 3rd, and 4th IMO GHG studies (IMO, 2009, 2015b, 2021)

^b The international shipping data from the IEA were accessed on July 15, 2023

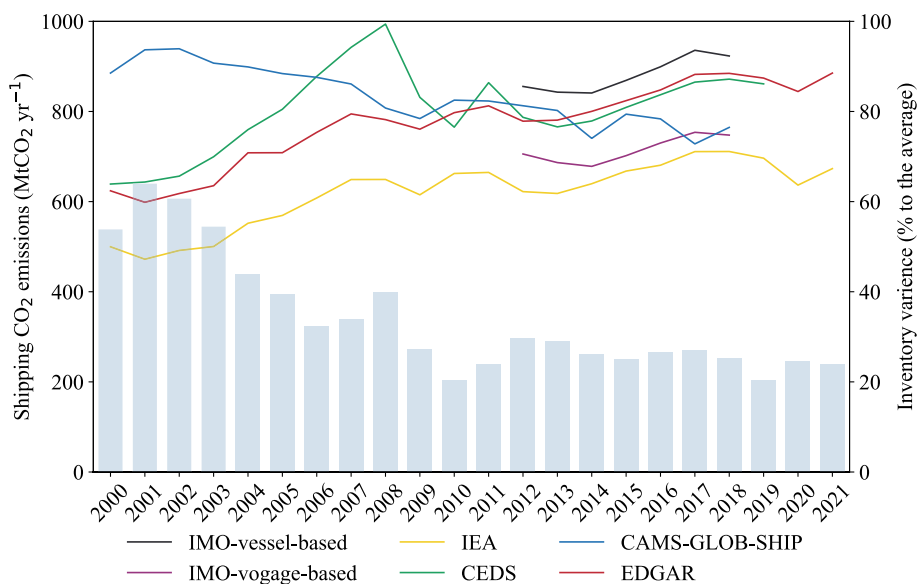


Fig. 1 Global CO₂ emissions from shipping 2000–2021. The lines represent historical CO₂ emissions (Mt yr⁻¹) from the emission inventories listed in Table 1, and the bars represent the ratios of variances between above emission inventories to their average values

3 Shipping emission uncertainties caused by calculation approach

As aforementioned, remarkable deviations are shown between different shipping emission inventories, of up to 20% of total emissions (Fig. 1). In fact, there is lack of transparency in shipping emission inventories, and one of the main concerns is the choice of

calculation method (Nunes et al., 2017; Kramel et al., 2021). To calculate ship CO₂ emissions, there are two main approaches that use different methods or models: bottom-up (activity-based) approach and top-down (fuel-based) approach. The schematic diagram of both modelling approach is shown in Fig. 2.

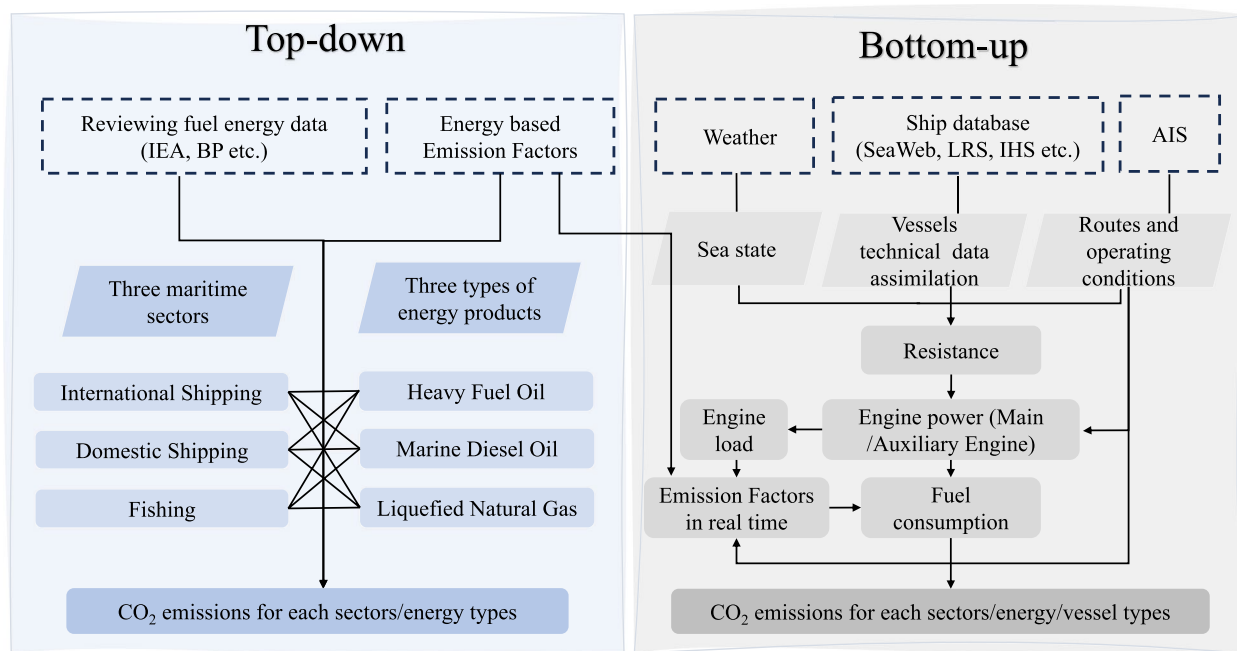


Fig. 2 Schematic diagram of the top-down and bottom-up modelling approach

3.1 Approach 1: top-down approach

The top-down approach is commonly used to prepare domestic and international emission inventories when it is not possible to obtain refined data traffic information (Miola & Ciuffo, 2011; Nunes et al., 2017). For example, the 2nd and 3rd IMO GHG studies, Corbett et al. (2009) and Endresen et al. (2003) applied this method to estimate early shipping emissions. This approach is based on marine fuel sales data and fuel-related emission factors, expressed as unit pollutants/unit fuel used. Therefore, the top-down approach is convenient without considering the vessels' characteristics. The IEA adopted this methodology to conduct a rapid review of shipping emissions trends in the post-pandemic era (IEA, 2023). In this case, the global emissions are calculated using Eq. (1):

$$CO_2 \text{ emissions} = \sum \text{fuel consumption}_i * \text{emission factor}_i \quad (1)$$

where fuel type i denotes fuel type, including Heavy Fuel Oil (HFO), Marine Diesel Oil (MDO), and Liquefied Natural Gas (LNG).

Marine fuel consumption datasets are usually derived from energy statistical reports of international energy organization and companies, such as the IEA, Energy Information Administration (EIA) and BP energy statistics. Accordingly, MDO is more carbon intensive, emitting 3.206 tons of CO₂ per ton of fuel used. If all MDO and HFO were to be replaced by LNG, CO₂ emissions from marine fuels would also be eliminated by 14% because of the low share of LNG (IMO, 2015a, 2015b). It is also clearly that the emission factors of CO₂ are relatively stable as a result of full fuel combustion and absence of carbon capture technologies. The uncertainty of the top-down method could mainly be attributed to the uncertainty of energy consumption statistics, especially misallocation and duplications happened in maritime industry reporting (IMO, 2021). Results deriving from this approach were later considered unreliable, but these initial studies did illustrate the shipping industry's impact on climate change. They also called attention to the issue of estimating uncertainty, which garnered scientific attention during the next 10 years (Nunes et al., 2017).

3.2 Approach 2: bottom-up approach

Bottom-up methods are based on data sources describing not only global shipping activity but also each registered ship's technical characteristics. Some bottom-up studies are based on fuel consumption data reported by operators regarding individual ships (Deniz et al., 2010; Howitt et al., 2010), while most recent studies applied the Automatic Identification System (AIS) to quantifying engine

operating hours, instantaneous speeds and travel times between points at sea, through high-resolution ships movement data (Jalkanen et al., 2009, 2016; Coello et al., 2015; Nunes et al., 2017; Kramel et al., 2021). The availability of AIS data has made it possible to describe the emitters in a more realistic manner, thus diminishing the uncertainty associated with fleet activities. Furthermore, with AIS data it is possible to present a high-resolution geographical information of emissions and investigate allocation of these emissions according to seasonality, ship type, flag states and ship routes. Once the vessel tech-characteristics are given, the exhaust emissions can be modelled on very high temporal and spatial resolutions. As in previous IMO GHG studies, the bottom-up method derives estimates of emissions by leveraging AIS-transmitted data to calculate the fuel consumption and emissions on an hourly, per-vessel basis, where individual ships are identified as 'in service' using the IHS database.

The AIS-based approach for shipping emission inventories was firstly proposed by Jalkanen et al. (2009), in which introduced the Ship Traffic Emission Assessment Model (STEAM). Followed by improvements in data-assimilation and realistic performance modeling, the STEAM2 (Jalkanen et al., 2012), STEAM3 (Johansson et al., 2017), SENEM (Moreno-Gutiérrez & Durán-Grados, 2021), and MariTEAM (Kramel et al., 2021) models have been subsequently released. Generally, the bottom-up calculation steps could be simplified as Eqs. (2), (3) and (4) based on Eq. (1):

$$\text{fuel consumption} = P_{\text{transient}} * t * SFOC \quad (2)$$

$$SFOC = SFOC_{\text{relative}} * SFOC_{\text{base}} \quad (3)$$

$$SFOC_{\text{relative}} = 0.455 LF^2 - 0.71 LF + 1.28 \quad (4)$$

where $P_{\text{transient}}$ is engine power for main engine (ME) and auxiliary engines (AE) delivered in real time during all the navigation; t is the time duration of the vessel in the area studied; $SFOC$ is the specific fuel oil consumption of per unit of time; $SFOC_{\text{relative}}$ is the ratio of actual fuel efficiency to maximum efficiency (from 1 to 0) that varies according to the engine load factor; LF for slow, medium, and high speed diesel engines (SSD, MSD, and HSD, respectively); and $SFOC_{\text{base}}$ is the maximum fuel efficiency defined by the manufacturers.

Consequently, the bottom-up approach could be seen as a byproduct of information technology, which calls for ship operation data (ship type and/or category; length, gross tonnage, breadth, and height; ship main engine (ME) and auxiliary engine (AE) power; ship operating speed; and engine-specific fuel consumption), shipping activity and traffic data (ship speed and acceleration

profiles; scheduled time of arrival and departure; engine operation); as well as other specific data (fuel type and emission factors) (Nunes et al., 2017). Inevitably, the so-called bottom-up approach—which estimates emissions at the level of a single vessel at a given location—is thought to be more accurate locally (Moreno-Gutiérrez et al., 2015; Moreno-Gutiérrez & Durán-Grados, 2021). From an energy consumption perspective, the bottom-up approach proved to perform better in collecting data on LNG fuel consumption, leaving a deviation of 9–10 Mt yr⁻¹ in LNG consumption to account for the uncertainty in EIs for shipping industry (IMO, 2021).

Apart from the estimation approach, the scope of research also affects the consensus on CO₂ emissions from shipping. Regarding research scopes, emission inventories could be further divided into on-site and lifecycle emission inventories. The on-site method presents emissions from the engine during ship operation, while lifecycle emission inventories cover up/down stream activity in the most emission-intensive

phases of fuel production (well-to-tank). Accordingly, raw material extraction, transportation, and processing might result in an additional 12% CO₂ emissions for the marine industry (Lindstad et al., 2020; Kramel et al., 2021).

4 Future emissions reduction measures

With the adoption of the net-zero target answering the 'where' question of a low-carbon transition in the shipping industry, the scientific community has made major efforts to propose and elaborate 'how' solutions. In this regard, Bouman et al. (2017), Xing et al. (2020), and Chris (2023) have reviewed the novel technologies, measures, and potential for reducing CO₂ emissions from shipping (Table 2). It shows that the margin of error for individual measure across studies is extremely large. In summary, the ultimate realization path of shipping decarbonization probably includes three kinds of paths:

Table 2 Measures and potential effect on CO₂ emissions reduction for marine industry

Type of measure	Main measures reviewed	Xing et al. (2020)	Bouman et al. (2017)	Chris (2023)	
Emission source control	Biofuels		25–84%		
	LNG	12–20%	5–30%		
	Hydrogen				
	Ammonia				
	Wind power		1–50%		
	Fuel cells		2–20%		
	Cold ironing	0–40%	3–10%		
	Solar power	0.2–12%	0.2–12%		
	Emission process control	Vessel size	2–30%	4–83%	
		Hull shape	2–10%	2–30%	6.4%
Lightweight materials		0.1–22%	0.1–22%		
Air lubrication		1–20%	1–15%	3.5%	
Resistance reduction devices		1–15%	2–15%	2.1%	
Ballast water reduction		0–10%	0–10%		
Hull coating		1–10%	1–10%	5%	
Hybrid power/propulsion			2–45%		
Power system/machinery		2–45%	1–35%	10.6%	
Propulsion efficiency devices		0–6%	1–25%	11%	
Waste heat recovery		0–5.4%	1–20%		
On board power demand		0.1–5%	0.1–3%		
Capacity utilization		5–50%	5–50%		
Voyage optimization		0.1–47%	0.1–48%		
Speed optimization		0–80%	1–60%	8.50%	
			1.70%		
			0.4%		
			1.7%		
Post-emission reprocessing	CCUS	0–70%			
	ETS				

- i) Emission source control, i.e., the use of low-carbon (e.g., LNG, methanol) or zero-carbon (e.g., hydrogen, ammonia) alternative fuels, as well as cleaner energy sources, such as electric power, wind power and solar power (Gilbert et al., 2014; Ushakov et al., 2019), in order to control carbon dioxide emissions at the source.
- ii) Emission process control, i.e., to further improve ship energy efficiency, especially if traditional fossil fuels continue to be used (Bouman et al., 2017). Technical and management measures can be taken to improve ship energy efficiency. Technical measures include optimization of hull line design, use of energy-saving and emission-reduction marine equipment, and adoption of new ship drag-reducing technologies (Miola & Ciuffo, 2011); and management measures include speed reduction for sailing (Corbett et al., 2009), route course optimization, optimization of navigational status (e.g., longitudinal inclination and draught), cleaning of the ship's hull, recycling of residual heat (Shu et al., 2017), and the use of shore power for berthing (Styhre et al., 2017; Chen et al., 2019).
- iii) Post-emission reprocessing, i.e., the use of Carbon Capture, Utilization, and Storage (CCUS) and other technologies to treat the emitted carbon dioxide (Zhou & Wang, 2014; Sarbanha et al., 2023).

Considering the mutual exclusivity and interdependence of measures, the maximum potential for emission reductions ranges from 75% to 85% in 2050 (Bouman et al., 2017). However, the two major challenges of economic and technological feasibility loom on the horizon and will significantly diminish proper expectations of the potential for emission reductions (Xing et al., 2020). In fact, only a 50–60% reduction based on emission source control and emission process control measures listed in Table 2 are realistic, leaving 40–50% abatement responsibility to be shouldered by zero-carbon fuels, CCUS, and out-of-industry transfers (Bouman et al., 2017). Currently, all three decarbonization pathways have achieved varying degrees of development, and in the long term, with the gradual maturation of the technology, the use of zero-carbon alternative fuels will become a good option. The short-term focus is on increasing the use of shore power and accelerating the piloting of electric boats, along with promoting the standardization of boat types; in the medium term, it will focus on promoting the use of new energy vessels, actively improving the operational energy efficiency of in-use vessels, accelerating the elimination of old vessels and improving the standardization of ship types (CWTRI, 2022). Overall, the increase in the proportion of electric ships is supposed to contribute

the most to CO₂ emission reduction, followed by ship enlargement, ship elimination, shore power use and operational energy efficiency.

5 Challenges of achieving net zero in the shipping industry

Given all the measures discussed in Section 4 could be applied completely, net-zero targets for shipping seems to be achievable. However, decarbonization of the shipping industry is not a stand-alone issue; it is rooted in the broader context of sustainable development. As such, comprehensive considerations should be made when selecting decarbonization options, and other GHG/hazardous gas emissions should not be disregarded for the sake of decarbonization. The negative effects of decarbonization may reflect in the fact that the retrofitting of CCUS marine gas scrubbers on existing ships will have a promoting impact on emissions of hazardous materials, such as polycyclic aromatic hydrocarbons (PAHs), elemental/organic carbons, and heavy metals (Sarbanha et al., 2023). As another example, LNG, as an alternative fuel, can reduce carbon dioxide emissions by about 25% compared to conventional heavy fuel oil, but fugitive methane occurs during the use of LNG (Bouman et al., 2017). In a nutshell, side effects of emission reduction measures need to be fully considered before they are put into operation.

Meanwhile, while green environmental conservation is one of the aims pursued by shipping, safety remains the major goal always that is followed by navigation. The purpose of the shipping industry is to provide safe, efficient and convenient transportation services, and without the guarantee of safety, nothing else is possible. Therefore, regardless of the decarbonization techniques implemented, navigation safety should be assured throughout the shipping decarbonization process. For example, among alternative fuels, hydrogen and ammonia are both zero-carbon fuels, and ships fueled by hydrogen or ammonia can realize a complete green transformation, but at the same time, hydrogen is explosive, and ammonia is toxic and corrosive, so how to use these two alternative fuels in a safe manner is an issue to which the industry must pay great attention. Although the International Code of Safety for Ship Using Gases or Other Low-flashpoint Fuels (IGF Code) provides an international standard and framework for the use of gaseous or low flashpoint fuels on board ships, the IGF Code currently only contains requirements for the use of LNG as fuel on board ships, and the requirements for the use of other alternative fuels have not yet been included in the IGF Code (IMO, 2015a, 2015b).

Furthermore, IMO has developed a 'Pricing Mechanism for Marine Greenhouse Gas Emissions,' the

timetable calls for approval carbon tax by 2025 and implementation by 2027. While a global market mechanism would go a long way toward preventing unequal treatments obtained in regional shipping ETSs (e.g., the EU ETS), a global carbon tax would impose an enormous cost on commodities and their transporters and, ultimately, on consumers. In the short term, container shipping lines ordering new ships are focusing on two alternative fuels (LNG and methanol) to reduce CO₂ emissions, both of which are much more expensive than traditional marine fuels. Numerous research have raised worries that mandatory ETS adoption may disrupt and undermine trade activities, thereby compromising the welfare of the crew (Bows-Larkin, 2015; Wu et al., 2022). Additionally, Wu et al., illustrated the challenges of determination of the free emissions quota percentage (FEQP) and the carbon trading price (CTP), management, and the common but differentiated responsibilities and equal treatment in the implementation of ETS (Wu et al., 2022).

To promote green fuels, a number of countries pledged at COP26, the United Nations climate conference, to establish green shipping corridors to promote the use of alternative fuels on board ships. A total of 24 countries, including the U.S. and the U.K., signed the declaration, working together to promote a shift to zero-emission shipping (UN New, 2021). However, with 97.6% of the global fleet currently using fossil fuels, there is still a long way to go in the green future. To achieve this, net-zero shipping necessitates coordinated design of routes and berths, intelligent and big data traffic regulation, further degradation of the private nature of shipping traffic, and avoidance of trade protectionism.

6 Conclusions

This paper provides a comprehensive review of decarbonization in the global shipping industry by reviewing emission inventories, estimation methods, emission reduction measures and operational challenges. The strengths and weaknesses of various emission indicators and estimation methods are analyzed, as well as the challenges of widespread adoption of emission reduction measures. Our findings show that there are significant differences in historical CO₂ emission trends due to uncertainties in estimation methods and the scope of the study. In contrast, IMO ship-based emission inventory estimates are higher, while CAMS-GLOB-SHIP v3.1 provides high-resolution information. The bottom-up life cycle approach is more favorable for using geospatial information to monitor and manage emission reductions across the industry.

CO₂ emissions from global shipping returned to pre-pandemic levels by 2021, which indicate that it is urgent

to improve energy efficiency so that seaborne trade can be decoupled from carbon emissions, thereby achieving a net-zero carbon emissions target for the shipping industry. For mitigating CO₂ emissions from shipping, emission source control and emission process control measures could offer 50–60% reduction potential, leaving 40–50% abatement responsibility to be shouldered by zero-carbon fuels, CCUS, and out-of-industry transfers. In detail, increasing the use of shore power and accelerating the piloting of electric boats are vital for medium- and long-term adoption of new energy. The increase in the proportion of electric ships is supposed to contribute the most to CO₂ emission reduction, followed by ship enlargement, ship elimination, shore power use and operational energy efficiency.

In addition to the widely discussed economic and technological feasibility, net-zero emissions in the shipping industry still face many constraints and challenges. One of the challenges is to avoid the side effects of decarbonization measures, such as fugitive methane from LNG utilization and PAHs exhaustion from CCUS. Another challenge is to guarantee navigation safety when considering zero-carbon but chemically unstable fuels. An international standard and framework for the use of hydrogen and ammonia require to be developed to provide guidance on how to properly store and burn these alternative fuels. Meanwhile, the adoption of global ETs should safeguard the well-being of the crew, and the free emissions quota percentage (FEQP) and the carbon trading price (CTP), international management should be further discussed. The importance of international cooperation for green corridors should also be further emphasized, and more coastal countries should be called upon to participate in the co-construction of clean power berths.

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Authors' contributions

Shiyu Deng: Data curation, Visualization, Formal analysis, Writing – original draft. Zhifu Mi: Supervision, Conceptualization, Writing – review & editing. Both authors read and approved the final manuscript.

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Not applicable.

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Competing interests

The authors declare that they have no competing interests.

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