Transition towards carbon neutrality: A structured review on current policies and measures in international shipping

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Abstract. Current studies lack a comprehensive understanding of the status of carbon emission reduction in international shipping from the perspectives of policies and measures, which tends to increase uncertainty in policy-making. The study aims to use a structured review approach to systematically collect and analyse carbon reduction policies as well as technical, regulatory, and economic measures in international shipping in recent years to support international shipping carbon neutrality decisions. The results show that most regions are committed to achieving zero emissions by 2050, but the reduction targets of international maritime organizations are lagging; while hydrogen, ammonia and green methanol fuels and ship wind power have a high potential to advance emission reduction, they are still limited by technology, regulation, cost and support; market-based trading measures can reflect emission reduction targets, but carbon prices are not yet mature; other measures also suffer from emissions shifting, low emission reduction potential or unsustainability. Tracking the progress of policies and measures to reduce carbon emissions in international shipping benefits to “know yourself as well as the enemy” for supporting decisions.

1 Introduction

International shipping, which is responsible for more than 80% of international trade freight, accounts for 2%-3% of global greenhouse gas emissions [1]; according to the International Maritime Organization (IMO) Fourth Greenhouse Gas Study, carbon dioxide (CO_2) emissions from international shipping will still increase by 50% in 2050 compared to 2018 and by 90-130% compared to 2008 while maintaining current policy levels [1].

To achieve the United Nations 2030 Sustainable Development Goals and the temperature control targets from the Paris Agreement, various initiatives have been put forward to reduce carbon emissions from international shipping in recent years, such as the IMO published the Initial IMO Strategy on Reduction of GHG (greenhouse gas) Emissions from Ships in 2018; the Ministry of Transport of the People’s Republic of China proposed to reduce carbon emissions per unit of transport turnover of operating ships by 3.5% in 2025 compared to 2020 [2]; the European Union proposed the “FuelEU” maritime initiative to set maximum limits on the GHG content of ship fuel [3]. However, has the policy pace of carbon reduction in shipping been consistent across regions in recent years and what are the differences? How about the corresponding measures against the backdrop of continuous updating of shipping carbon reduction policies?

Currently, only a few scholars kept eyes on relevant policies and measures to reduce carbon emissions from shipping, e.g., Bouman, Lindstad [4] and Balcombe, Brierley [5] attempted to assess the potential of emission reduction measures; Serra and Fancello [6] provided a preliminary discussion of possible scenarios and challenges for reducing emissions from shipping by 2020; Xing, Spence [7] overviewed the concepts, approaches, characteristics, barriers, and prospects of abatement measures for ships. However, they are fragmented or outdated in understanding the abatement policies and measures for shipping carbon emissions. This study, therefore, uses a structured review method to systematically collect relevant information and analyze the abatement progress across regions. It will help decision-makers and scholars to gain a comprehensive understanding of carbon emissions reduction strategies in international shipping, and provide a knowledge base for carbon neutrality in shipping.

2 Methods and materials

A literature review has been regarded as an important tool for knowledge management, helping to collect and assess existing knowledge and identify research questions to develop and expand relevant knowledge to support decision-making [8]. A structured, procedural, replicable literature review method contributes to exploring knowledge scientifically and rigorously [9]. This study therefore uses the structured review method to systematically collect and analyse the current status of carbon reduction policies and measures in international

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shipping for knowledge management. The first step is to collect and refine the information from literature databases and relevant official websites by using keyword searching and then extracting the key content for further analysis [10].

In this study, the databases of the Web of Science (SCI) and China National Knowledge Infrastructure (CNKI), which cover a wide range of literature in both English and Chinese, are selected. The keywords "maritime OR shipping OR marine transportation AND carbon" and "海运+航运+海洋运输 AND 碳排放+碳减排+低碳+零碳+脱碳" are respectively used for the SCI and CNKI abstract searching. The time range was set in 2018 because it is an important phase following the release of the IMO's initial reduction strategy and it can help to verify the process and effectiveness of the strategy's implementation. After excluding the News and Meeting Abstract and those papers belonging to research areas of physical sciences, life sciences, and arts and humanities and merely focusing on aviation, inland waterways, naval vessels, or submarine cables without mentioning shipping policies and measures based on their titles and abstracts, there were 83 articles from SCI remained for further studies on May 31, 2022; the CNKI refinement, which excluded the News and abstracts and those papers focusing on aviation, inland waterways, Sulphur emission, or black carbon, without mentioning shipping policies and measures according to their titles and abstracts, kept 102 articles on the same day. On the other hand, related international and regional organizations are also selected and searched based on experts' consultations (shown in Table 1).

Table 1. Relevant organizations for data collection.

International	IMO
	International Transport Forum (ITF)
	Global Maritime Forum (GMF)
	International Council On Clean Transportation (ICCT)
	International Chamber of Shipping (ICS)
Regional	European Federation for Transport and Environment (T&E)
	European Commission
	United Kingdom government
	Ministry of Transport of the People's Republic of China
	United States Environmental Protection Agency
	Maritime and Port Authority of Singapore
	Ministry of Land, Infrastructure, Transport and Tourism, Japan
	Ministry of Oceans and Fisheries, South Korea
	Norwegian Shipowners' Association
	Lloyd's Register of Shipping
	American Bureau of Shipping
	China Classification Society
Consultancies	University Maritime Advisory Services (UMAS)
	CE Delft
Companies	Maersk
	Wärtsilä
	ExxonMobil

As initial results, we can find the literature from databases paid much attention to a variety of specific measures on carbon emission reduction for shipping such as alternative fuel use [11, 12], carbon capture technologies [13, 14], energy efficiency management [15], and carbon tax [16]. Both topics from the two databases are very similar. As for the organizations' knowledge, we can see the IMO guides the carbon emission reduction from shipping by proposing not only specific abatement targets but also short, medium and long-term measures [17]; the ITF, an international inter-governmental organization in the transport sector, also published a pathway towards zero-carbon shipping [18]; other international organizations including GMF, ICCT, and ICS discussed the policies and potential options for approaching the carbon reduction ambition [19-21]. Additionally, regional organizations aim to issue detailed policies or measures as well as abatement routes [22] and consultancy organizations represented by CE Delft and UMAS have carried out much research in recent years to support them [3, 23, 24]. Companies mainly integrated shipping carbon reduction into their corporate social responsibility reports.

3 Results

Based on the above data collected, this study summarizes the carbon emission reduction policies in international shipping since 2018 as well as specific measures from technical, management, and economic aspects based on their characteristics. The technical measures focus on improving the abatement technology, process, equipment, or materials; the management ones tend to help achieve the carbon emission reduction targets through planning, organizing, coordinating, and controlling; and the economic measures are characterized by market or economic pathways.

3.1. Current policies for carbon abatement in international shipping

3.1.1 International policies

In 2018, the IMO set an initial target to reduce the greenhouse gas emissions from ships, namely to reduce the global carbon intensity of shipping by at least 40% by 2030 compared to 2008, and to strive for a 70% reduction by 2050; and to reduce total greenhouse gas emissions from shipping by at least 50% by 2050 compared to 2008, and to strive for zero greenhouse gas emissions in this century [25].

3.1.2 Regional policies

Regional policies on carbon abatement in international shipping can be shown as follows:

- Europe: In recent years, through the European Green Deal, the European Commission has proposed the EU's greenhouse gas emissions will be at least 55% of the 1990 level by 2030 and carbon neutral by 2050 [26].

- UK: The UK government encouraged investment in maritime infrastructure to promote the use of carbon-neutral fuels and renewable energy to ensure that the IMO target of a 50% reduction in maritime GHG emissions by 2050 can be achieved [27].

- China: In September 2020, China announced its "Carbon Peaking, Carbon Neutrality" target, i.e., peaking carbon emissions by 2030 and achieving carbon neutrality by 2060.

- USA: The United States government rejoined the Paris Climate Agreement in January 2021 and proposed to reduce the GHG emissions by 50-52% of 2005 levels by 2030; achieve a 100% carbon-free electricity by 2035 and a net-zero economy by 2050 [28].

- Singapore: In March 2022, the Singapore Maritime Decarbonization Blueprint: Towards 2050, published by the MPA, proposed a transition to a low-carbon future through the use of cleaner energy, automation and digitalization by 2030; and a net-zero emission economy by 2050 [29].

- Japan: In March 2020, through the release of the Roadmap to Zero Emissions from International Shipping, Japan proposed that by 2030, the carbon intensity of international shipping will be reduced by at least 40% compared to 2008; by 2050, total annual GHG emissions from international shipping will be reduced by at least 50% compared to 2008; and as soon as possible in this century, GHG emissions from international shipping will cease [30].

- South Korea: In 2020, the South Korean government released the 2030 Green Ship-K Initiative to enable to gradual reduction of 70% of GHG emissions in 2030 in ship design, future fuels, renewable energy, and equipment by exploring advanced emission-free technologies emissions by 2030, and towards net zero emissions by 2050 [31].

- Norway: Norway has adopted a national plan to reduce GHG emissions by 40% in 2030 compared to 1990 and to become a low-emission society by 2050 [32]. In addition, members of the Norwegian Shipowners' Association will reduce GHG emissions from ships by 50% by 2030 compared to 2008, order only ships with zero-emissions technology from 2030 onwards, and have a zero-emissions fleet by 2050 [33].

3.2 Current measures for carbon abatement in international shipping

3.2.1 Technological measures

The existing technical measures to reduce carbon emissions from international shipping can be presented as follows:

(1) Alternative fuel technologies

- Introduction: Current alternative fuel technologies cover LNG, biofuels, methanol, hydrogen and ammonia [23].

- Implementation: By 2018, over $500 million had been invested in EU LNG offshore bunkering projects [34]; biofuels and methanol have been tried since around 2009 and 2015 respectively, while hydrogen and ammonia fuels from around 2019 and 2020 respectively [23].

- Advantage and disadvantage: On a life-cycle basis, the use of LNG can reduce emissions by 18% more than conventional fuels [11], but it's difficult to achieve the IMO's emission reduction targets [34, 35] and prone to leakage problems [36]; Conventional biofuels also do not reduce carbon emissions due to the destruction of forests and grasslands, but advanced biofuels can reduce carbon emissions significantly [37]. Grey methanol, produced from natural gas, produces more greenhouse gases, but green methanol, produced from the fusion of hydrogen and CO2, is considered an important carbon-neutral option [37]. Hydrogen and ammonia are zero-emission fuels, but are flammable and toxic, posing safety risks [37].

- Barriers: Uncertainties in regulatory regimes, low technology maturity, high production costs, restricted supporting infrastructure and high retrofitting costs have hindered the progress of alternative fuel use [12, 23].

- Future pathways: The emission reduction effect of using LNG is considered to be temporary [34]. Although technologies for biofuel and methanol are developing rapidly, they do not provide sufficient emission reductions and are considered to be a "bridge" fuel [37]. It is expected that hydrogen and ammonia marine engines will be commercially available on a large scale by the mid-21st century [37].

(2) Engine technology

- Introduction: Reducing carbon emissions by limiting engine power [38] or increasing the thermal efficiency and intelligence of the engine [7].

- Implementation: Advanced and intelligent engine management, common rail or electronically controlled fuel injection, variable geometry turbochargers, fuel slide valve upgrades, and cylinder fuel consumption optimization are currently being used to improve engine efficiency [7]. Limiting engine power is also considered a simple way to meet EEXI requirements for older ships with few modifications to the ship and no impact on basic performance [38], and amendments to the engine power limitation guidelines have been approved by IMO [39].

- Advantage and disadvantage: The use of advanced and intelligent engine technology has now almost reached the limit of energy efficiency, with less than 1% potential for further fuel savings [7]; as current ship operating speeds are already well below maximum speed, CO2 reductions are hardly proportional to engine power limits, and only a power limit of more than 50% will reduce CO2 emissions from existing ships to below the expected 2030 level [38].

- Barriers: There is less scope for emission reductions with advanced and intelligent engines [7] and mandatory engine power limits [38].

- Future pathways: Flexible engine power options, such as hybrid and electric propulsion, may be considered in the future [7].

(3) Ship propulsion technology

- Introduction: Improve ship propulsion design [40] or use wind propulsion technology [7] to reduce energy consumption.

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- Implementation: Shipping companies are focusing on improving the design of ship propulsion units [40]; wind propulsion is still in the early stages of development or testing [18].

- Advantage and disadvantage: Optimized design of ship propulsion units may improve energy efficiency by up to 15% [40]; wind energy has a high potential for fuel savings as a renewable energy source.

- Barriers: Wind propulsion technology is still immature and has high installation and operating costs [18].

- Future pathways: Studies predicted that wind propulsion systems will gradually gain acceptance from 2025 onwards, despite the relatively low maturity of the market [18].

(4) Carbon capture technology

- Introduction: The captured CO2 is liquefied and stored temporarily on board a ship and then transported to a storage site for sequestration or reuse [13].

- Implementation: This technology has now been tried on LNG vessels [13]. Post-combustion carbon capture processes have been explored [41], as well as membrane and solvent-based carbon capture technologies [14, 42].

- Advantage and disadvantage: The technology can be implemented in the short term and has the potential to reduce CO2 emissions from the maritime industry by 65% [13, 43].

- Barriers: The technology faces high investment costs, limited space on board, and a lack of full-scale industrialization [43].

- Future pathways: It is still in the development and demonstration phase but will play an important role in reducing emissions due to its significant emission reduction and ship suitability [44].

(5) Hull antifouling technology

- Introduction: Reducing hull roughness and improving energy efficiency in shipping [5].

- Implementation: Significant funding is currently being invested in antifouling paints to prevent bacteria from adhering to the hull to reduce hull drag [5].

- Advantages and disadvantages: Modern paints are divided into biocides, which tend to affect the environment, and biocide-free paints, which suffer from non-stick, relatively expensive and insufficient durability [5].

- Barriers: Existing coatings face challenges in terms of performance, cost, ease of application and ecological impact [5].

- Future pathways: More suitable coatings, such as fish mucus-based excavations, will be explored in the future [45].

(6) Shore power technology

- Introduction: Ships are powered by shore-based electrical systems while in port, shutting down auxiliary engines and reducing energy consumption [46].

- Implementation: Some dozens of ports currently have shore power facilities. 80% of the energy used by certain types of ships in port in 2020 will come from shore power or similar environmentally friendly sources [46].

- Advantage and disadvantage: The measure has the advantage of being implementable in the short term [46]. Studies have shown that the implementation of shore power can reduce carbon emissions by between 3% and 60% [46].

- Barriers: The implementation of shore power facilities is influenced by their compatibility, financial cost of construction, and public acceptance [46].

- Future pathways: Core EU ports are required to establish shore power or LNG fuel supply facilities by 2025, and other countries are following this measure [18], but the economic incentives and regulatory framework are still under discussion [7, 47].

Of these, the use of hydrogen ammonia fuels and green methanol, ship wind propulsion technology and use of non-hazardous paints have high potential for emission reductions, but are currently difficult to implement; engine technology, ship propulsion design and carbon capture technology have less potential for emission reductions and are short-term in nature; from a whole life cycle perspective, Liquefied Natural Gas (LNG) technology, biofuels, grey methanol and shore power technologies may be susceptible to other GHG emissions or emissions displacement and are characterized as transitional measures.

3.2.2 Management measures

The existing management measures to reduce carbon emissions from international shipping can be presented as follows:

(1) Scheduling optimization,

- Introduction: Optimizing the scheduling of ships, containers, berths, shore bridges, and yard bridges can reduce energy consumption by increasing efficiency [48].

- Implementation: Scheduling optimization algorithms incorporating carbon emission targets are still under development [7, 43]; there is a strong appetite for optimized scheduling among shipping companies and terminal operators [7].

- Advantage and disadvantage: It is beneficial to reduce ship turnaround times and improve service efficiency and competitiveness [7].

- Barriers: How to carry out multi-objective optimization is an obstacle to optimal scheduling in the context of carbon reduction [48, 49].

- Future pathways: Further improving the quality of the algorithm under uncertainty and optimizing scheduling from a multi-objective perspective [48].

(2) Speed optimization

- Introduction: Reducing carbon emissions by reducing the speed at which ships sail [7].

- Implementation: In a sluggish shipping market with excess capacity, slow sailing has been used as an important option to save fuel [7].

- Advantage and disadvantage: Since speed is a cubic function of power and fuel consumption, slow sailing can reduce fuel consumption [15], but long-term slow sailing can form carbon deposits to affect diesel engine efficiency and increase CO2 emissions [50]. Slow sailing can increase voyage time and reduce vessel transport workload, resulting in lost revenue [51]; it also has the potential to lead to an expansion of the world fleet and increased competition; and is less likely to promote technological innovations that reduce emissions [7].

- Barriers: Slow sailing is constrained by factors like voyage frequency, charter time, customer demand, and additional operating costs [7].

- Future pathways: Studies advised that slow sailing can be implemented within a regulatory framework based on fair market and voluntary action, but need not become mandatory [7].

(3) Fleet deployment and route optimization

- Introduction: Fleet deployment is about minimizing the time and cost of transport within environmental constraints [52]; route optimization considers the allocation of ships in the context of carbon emissions [53], and the selection of routes with minimal ship resistance and calm weather conditions [7].

- Implementation: Research has begun to explore multi-objective fleet deployment and route allocation planning models that incorporate carbon reduction [52, 53]; weather forecasting systems have also been widely developed and applied to shipping companies [7].

- Advantage and disadvantage: Fleet deployment and route allocation optimization models that take into account carbon emission reductions can contribute to low-carbon decision-making in shipping [52, 53]; reducing vessel resistance to navigation and integrating sea and weather conditions into routes can help save energy [7].

- Barriers: Optimization models and weather route forecasts that consider carbon emissions still have limitations [52, 54].

- Future pathways: The model and the accuracy of weather route prediction will be improved and practical applications will be attempted [52, 54].

(4) Energy efficiency management

- Introduction: Improving the energy efficiency of ships and saving energy to reduce carbon emissions [55].

- Implementation: This is carried out based on rules, including EEDI, Ship Energy Efficiency Management Plan (SEEMP), Energy Efficiency Operational Indicator (EEOI), Energy Efficiency Performance Indicator (EEPI), EEXI and CII [7, 55-57]. At this stage only EEDI and SEEMP are mandatory [7]; EEXI and CII will be implemented from 2023.

- Advantage and disadvantage: The rules-based energy efficiency management can contribute to global maritime governance [7]. However, the existing rules still do not maximize the efficiency of the global fleet [57]. For example, due to the prevalence of deceleration, the engine load of most ships is much lower than the engine load allowed by EEXI, so EEXI has little effect in reducing emissions [56]; due to the slow renewal of ships and the small proportion of new ships, EEDI implementation will only reduce emissions by about 2% by 2030 [7].

- Barriers: If EEDI is implemented on existing ships, it is limited by financial support, although it may bring 1%-6% emission reductions by 2030 [7]. While SEEMP is mandatory for new or existing ships on board, it currently relies on the voluntary setting of energy efficiency targets and self-monitoring [55]. Other targets have not been agreed due to a lack of commercial data or scientific value [55].

- Future pathways: In line with the IMO emissions reduction process, attention will be given in the short term to implement the existing ship EEXI and ship CII rating mechanisms [17]; and further refinement of EEDI and SEEMP [17].

(5) Monitoring and forecasting

- Introduction: Predicting and monitoring carbon emissions from shipping is used to support carbon reduction decisions.

- Implementation: Scenario analysis is used to predict carbon emissions from ships based on automated ship identification systems [58], multivariate interactive grey models [59], and energy consumption [60]. Besides relying on energy statistics, ship fuel consumption data collection systems and emission monitoring reports near real-time shipping emission monitoring are also being explored [61].

- Advantage and disadvantage: Predicting and monitoring shipping carbon emissions can help to quantitatively support international shipping carbon reduction decisions.

- Barriers: Data limitation and sensitivity, as well as the complexity, uncertainty, and accuracy of results may affect the reliability and effectiveness [61].

- Future pathways: The accuracy and reliability of forecasting and monitoring are continuously improved [62].

(6) Assessment and evaluation

- Introduction: Assessing the international shipping carbon reduction measures can help shipping carbon reduction decisions.

- Implementation: The reduction measures were assessed through techno-economics [63, 64], cost-effectiveness [65], life cycle [66], climate impact [23], and multiple objectives [67].

- Advantage and disadvantage: Assessing the shipping carbon reduction measures helps to judge their availability and adaptability, but the accuracy needs to be improved, and the activity-based ship emission inventories are underestimated [68].

- Barriers: Lack of basic data [69], uncertain parameters [66] and case study support [67] may affect the assessment and evaluation.

- Future pathways: Overcoming the barriers to the assessment and evaluation.

To sum up, most of these measures optimize the allocation of resources and improve energy efficiency. In contrast, the optimization of scheduling, speed, fleet, and route is more likely to be supported by stakeholders, but is limited by the accuracy and reliability of the model; the implementation of the commanding and mandatory energy efficiency management measures has pressure, but they are conducive to achieving phased progress in emission reduction; the monitoring and forecasting as well as assessment and evaluation are as supportive decisions tools.

3.2.3 Economic measures

The existing management measures to reduce carbon emissions from international shipping can be presented as follows:

(1) Emissions taxes and levies

- Introduction: A corresponding fee that is pre-set on fossil fuel consumption or CO2 emissions and requires market actors to pay for their emissions [20].

- Implementation: By May 2022, 36 carbon tax policies have been implemented globally [70]. Studies estimated that to achieve a 50% reduction in GHG emissions by 2050, the carbon price should be US$173 per ton. To achieve the 2050 target, the carbon price should be US$191 per ton, while the current carbon price is much lower [20].

- Advantages and disadvantages: The value of carbon emission limits in container shipping and total transport costs are negatively correlated, and higher carbon taxes can have an impact on the choice of maritime transhipment ports [71]; maritime carbon tariffs can hurt economic development, trade exports and welfare levels [72].

- Barriers: The emissions taxes and levies are largely determined by policymakers, making it difficult to reflect emission reductions and secure emission reduction targets [20]; uncertain taxes and levies also tend to influence business decisions [20].

- Future pathways: Setting prices that are commensurate with emission reduction targets [37]; to reduce price uncertainty, price bands can be set [20].

(2) Feebates

- Introduction: A variant of a tax or levy that sets benchmarks for emissions and carbon intensity, with a rebate if emissions are below the benchmark and a levy if they are above [20].

- Implementation: IMO short-term measures of carbon reduction can provide a basis for benchmarking the rebate, for example by setting an operational efficiency benchmark based on annual operational CII or using EEXI for benchmarking technical efficiency [20].

- Advantage and disadvantage: The tax and fee mechanism could easily lead to or exacerbate a two-tier market as low-emitting ships would be rewarded and high-emitting ships would be financially burdened by penalties [20].

- Barriers: It is difficult to ensure that environmental objectives are met; the feasibility and environmental benefits of a charging mechanism depend largely on the ability of the regulator to set benchmarks and rebates [20].

- Future pathways: Benchmarking tax and fee mechanisms is an important issue to address in the future [20].

(3) Emissions trading system (ETS)

- Introduction: A quantitative instrument with an emissions target or baseline set by the regulator, but not including a carbon price [20]. The measure is divided into (i) cap-and-trade systems, which fix an emissions cap and regulate emissions by auctioning or allocating emission allowances; and (ii) baseline and credit systems, which set a baseline for emission levels and issue credits to entities below the baseline level to bank or sell [20].

- Implementation: By May 2022, a total of 32 ETS policies had been implemented globally [70]. The EU began discussions in 2007 to extend its ETS to the maritime sector [73], but draft legislation to include shipping in the EU ETS had not been adopted by May 2022.

- Advantage and disadvantage: Cap-and-trade systems can achieve emission reductions quickly and cheaply, with a high degree of certainty about the effect of reductions [20]. A baseline and credit system can provide participants with an incentive to keep emissions below the baseline and avoid buying permits for excess emissions, and further reduce emissions and generate marketable credits [20]. However, the implementation of an ETS will increase costs and a market-determined carbon price may also lead to price volatility, increasing market uncertainty and business risk [74].

- Barriers: Geographical scope restrictions and the method of allocating emission allowances can easily hinder ETS implementation [73].

- Future pathways: Setting baselines related to environmental targets [37]; introducing price corridors to reduce uncertainty in carbon prices or allowances, and establishing accurate monitoring and enforcement systems to avoid non-compliance and cheating [20].

(4) Subsidies

- Introduction: Reducing the cost of zero-emission fuels by subsidizing fuel production and research and development costs [20]. Subsidies can be implemented through cash payments, tax breaks or direct financial support [20].

- Implementation: Most members of the Organization for Economic Co-operation and Development currently provide subsidies through tax breaks and fiscal advances, including tonnage taxes, special fiscal treatment for seafarers and ship fuel exemptions [20].

- Advantage and disadvantage: It helps to reduce the price of zero-emission technologies and fuels, stimulates research development and innovation, and closes the competitive gap [20], but tends to create overproduction of goods; manufacturers also risk making profits through subsidies rather than reducing the price of their products [20].

- Barriers: The lack of systematic data makes it difficult to ensure that subsidies are comprehensive, fair and transparent, thus affecting the effectiveness of subsidy policy implementation [47].

- Future pathways: Improving the transparency of subsidies [47] and, where possible, paralleling them with other policies and regulations [37].

By contrast, emissions taxes, levies and feebates are mostly price-setting measures by policymakers, which have a direct effect on emission reduction, but are less likely to correspond to emission reduction targets and to lead to a situation where “the strong are stronger and the weak are weaker”, affecting market competition; subsidies can avoid distortions in market competition, but they are not sustainable and can easily lead to overproduction of commodities or diversion of subsidies; ETS incorporates the market and helps stimulate the initiative to reduce emissions, and the certainty of ETS's emission reduction effect is stronger, but the current low

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carbon price makes it difficult to guarantee the achievement of emission reduction targets.

4 Discussion

As for the policy objective of carbon emission reduction in international shipping, most regions are committed to achieving zero emissions and carbon neutrality by 2050, while the IMO's emission reduction target is relatively lagging, which may hinder the Paris Agreement's goal achievement of temperature control of 1.5°C. For this reason, the ICS and countries such as the UK, the US, China, Japan and Norway have proposed to adjust the IMO's initial strategic goal of emission reduction to achieve zero emissions from international shipping by 2050 [75]. At this stage, the IMO is mainly promoting the emission reduction process by improving energy efficiency and carbon intensity targets, while the EU, the UK, Singapore, Korea, and other regions have started to explore renewable, clean energy or alternative fuels to promote zero emissions from shipping; in addition, the ETS has been extended to shipping by the EU first. Overall, policy objectives and initiatives to reduce carbon emissions from international shipping are being strengthened and advanced.

Measures that have relatively minor changes to existing ships and operational mechanisms, such as engine technology, ship propulsion plant design technology, hull anti-fouling technology, and the optimization of scheduling, speed, fleet, and route, are relatively easy to implement for achieving emission reductions through fuel savings and energy efficiency improvement in shipping, but are currently limited by advancing technology and optimization models to affect their emission reduction potentials; if carbon capture devices are retrofitted, the additional business operating costs will need to be considered; the LNG technology and grey methanol are less effective in reducing emissions due to incomplete combustion or leakage of greenhouse gases or pollutants; biofuel and shore power technologies are essentially equivalent to emissions displacement, and there is uncertainty about their effectiveness from a life-cycle perspective. It can also be observed that in recent years there has been a growing interest in hydrogen, ammonia and green methanol renewable energy use and market-based measures (e.g., ETS), in addition to the active response and promotion of IMO mandatory energy efficiency management. Among these, truly clean or renewable energy sources are bound to be an important solution to decarbonising shipping and effectively achieve zero emissions but are still limited by technology, regulation, cost, and support [12, 18, 23]. While ETS can draw on market forces as opposed to taxes and subsidies and correspond to emission reduction targets, uncertainty about the price of carbon, geographical scope limitations and the allocation of emission allowances [73] have hindered their implementation, and draft legislation to including shipping in the ETS in the EU region has not yet been adopted and remains resistant. We take nature-based solutions that are inspired by or learn from nature [76] and market-based tactics as priorities for reducing added negative interventions to ecosystems and society.

As a shipping industry serving the international trade economy, carbon emission reduction from shipping has been a hot topic in shipping management in recent years in the context of the Sustainable Development Goals and the Paris Agreement temperature control targets. While this study provides a comprehensive collection of information from literature databases and relevant organizations, it focuses only on progress and the status of representative regions from 2018 to May 2022 due to time and resource constraints. The 78th IMO Marine Environment Protection Committee meeting in June 2022 also discussed carbon reduction from shipping, including support for EEXI, SEEMP and CII implementation, advancing impact assessments and mid-term mitigation measures, and revising the initial strategy for carbon reduction in shipping, which still require further follow-up. Although international shipping involves multiple administrative jurisdictions, geographic regions and disciplines, and carbon reduction policy measures are difficult to advance, the overview in this paper shows that efforts are being made by many parties, especially for the research and development of renewable energy technologies, the mandatory implementation of energy efficiency targets and the promotion of ship emissions trading systems.

5 Conclusion

Carbon emissions from international shipping threaten global climate change and ecosystem health, yet the current pace of their reduction remains slow. Through a structured review of literature databases and relevant organizations' websites, this study collects and compares the international and regional policies as well as technical, management, and economic measures of carbon emission reduction in shipping to support decision-making and academic research.

The study found that most of the regional emission reduction targets tend to be zero-emission or carbon-neutral by 2050, which is more stringent than the initial strategy targets for emission reduction released by IMO in 2018. To meet the Paris Agreement's 1.5°C temperature control target, many regions are putting pressure on IMO to revise their emission reduction strategies in mid-2023. Regions have explored renewable and low-carbon fuels and incentives to reduce emissions, but are still at the initiative and planning stage. Specifically, hydrogen, ammonia and green methanol fuels and ship wind propulsion technology measures have high emission reduction potential, but are still limited by technology development, regulatory regimes, cost investment and the level of supporting facilities; engine technology, ship propulsion technology, hull anti-fouling paint technology and shipping optimization management are relatively easy to implement, but have limited emission reduction potential; LNG technology, biofuels, grey methanol and shore power technology are also relatively easy to implement but their potentials in emissions reductions are limited from a full life cycle perspective; carbon capture technologies are constrained by cost; and the tax system tends to lead to distorted market competition and is not conducive to sustainable economic incentives; the ETS, an entirely market-dependent trading system, is also underdeveloped due to the impact of low and uncertain carbon prices. Tracing the nature of shipping carbon neutrality that aims to sustain the ecosystem and society, it is recommended to take nature-based and market-based solutions as priorities for avoiding unpredictable impacts.

Although this study focuses only on the last five years of relevant information and policies of shipping representative regions due to time and resource constraints, it is a critical period since IMO's breakthrough release of its initial emission reduction strategy and it can also reflect important progress in carbon reduction in international shipping. Nevertheless, we will further track the latest progress of international shipping carbon reduction policies and measures, and try to assess the specific impacts caused by the implementation of international shipping carbon reduction measures, including the economic costs of inputs and the external ecological benefits they generate, to support scientific decision-making on the economic incentives for international shipping carbon reduction and improve the efficiency and effectiveness of policies and measures.

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