frontiers | Frontiers in Marine Science

TYPE Original Research
PUBLISHED 24 February 2023
DOI 10.3389/fmars.2023.1119663

OPEN ACCESS

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SPECIALTY SECTION
This article was submitted to Marine Affairs and Policy, a section of the journal Frontiers in Marine Science

RECEIVED 09 December 2022
ACCEPTED 13 February 2023
PUBLISHED 24 February 2023

CITATION
Zhang Q, Chen C, Zheng J and Chen L (2023) Quantitative evaluation of China's shipping decarbonization policies: The PMC-Index approach.
Front. Mar. Sci. 10:1119663.
doi: 10.3389/fmars.2023.1119663

Quantitative evaluation of China's shipping decarbonization policies: The PMC-Index approach

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In the past few decades, ship-source GHG emissions have increased significantly. As a large country with massive shipping activities, China has issued a number of governmental policies with the aim of promoting shipping decarbonization and achieving green shipping. This study adopts the Policy Modeling Consistency Index (PMC-Index) approach to quantitatively evaluate 15 representative policies that are dealing with shipping decarbonization affairs to different extents in China. The results show that there exists an overall good policy consistency with the average PMC index scoring 6.26, but all studied policies have certain aspects to be further improved. By reviewing these representative policies, it reveals that more emphasis has been placed by the Chinese government on the development and application of clean energy, coordination between shipping and port industries, and governance mechanism for shipping decarbonisation issues. In addition, two policy implications are draw for policy-makers in China.

KEYWORDS

decarbonization, green shipping, policy evaluation, policy modeling consistency, emission control

1 Introduction

As the backbone of the global economy, maritime transport enables the smooth operation of global logistics supply chains but also generates various negative externalities such as greenhouse gas (GHG) emissions (Grzelakowski et al., 2022). In the past few decades, ship-source GHG emissions have increased significantly. According to the second and fourth GHG studies of International Maritime Organization (IMO), total shipping GHG emissions had climbed from 1,046 million tonnes in 2007 to 1,076 million tonnes in 2018 (IMO, 2009; IMO, 2020). It is estimated that maritime transport accounts for 3% of the world's anthropogenic GHG emissions roughly (Lindstad et al., 2021). To mitigate global climate change, shipping decarbonization has been emphasized by various stakeholders including carriers, cargo owners, and regulators (Wan et al., 2018). Particularly, IMO, as the United Nations specialized agency that is responsible for global shipping safety and security and prevention of pollution by ships, has issued a series of policies to reduce GHG emissions from ships (Herdzik, 2021). Due to the polycentric nature of environmental governance, which indicates that there exist a number of multiple centers of decision making and each of them operates with some degree of autonomy, thus regional and local policies are also important for shipping decarbonization (Gritsenko, 2017).

As a large country with massive shipping activities, China has issued a number of governmental policies with the aim of promoting shipping decarbonization and achieving green shipping. For example, China promulgated "*The 14th Five-year Development Plan for Green Transportation*" in 2021, in which numerous measures such as development of clean energy powered ships and usage of shore power were highlighted to reduce GHG emissions from ships and port operations. However, till now there are no studies focusing on the evaluation of China's shipping decarbonization-related policies. From the perspective of policy improvement, it is actually necessary to holistically evaluate those shipping decarbonization policies and figure out their policy strengths and weaknesses. By doing so, we can better understand China's policies on shipping decarbonization. To this end, the current paper devotes to conducting the quantitative evaluation of China's relevant shipping decarbonization policies by applying the "Policy Modeling Consistency Index (PMC-Index)" approach, which concentrates on the policy consistency assessment with consideration of important policy variables as many as possible from various perspectives. The major contributions of this study are two-fold. First, PMC-Index model is introduced and applied to evaluate policies quantitatively in the domain of shipping decarbonization. Second, several characteristics of China's shipping decarbonization policies are identified.

The remainder of the present paper is organized as follows. Section 2 presents existing literature on shipping decarbonization policies worldwide and policy evaluation. In Section 3, the PMC-Index model is introduced in detail, and the studied China's representative shipping decarbonization policies are listed. The quantitative evaluation of the studied policies is conducted by constructing the PMC-Index model in Section 4. Section 5 further discusses China's shipping decarbonization policies beyond the results of the PMC-Index approach. Section 6 concludes the paper.

2 Literature review

2.1 Shipping decarbonization policies

Due to the challenge of global warming and the critical role that maritime transport plays in GHG emissions (Alamoush et al., 2020), shipping decarbonization policies have attracted increasing attention from academia and industry in recent years. Notably, IMO plays a vital role in reducing GHG emissions from ships (Grzelakowski et al., 2022). To show IMO's ambition and strategies to address GHG emissions from international shipping, the resolution "*Initial IMO strategy on reduction of GHG emissions from ships*" was adopted by the 72th session of the Marine Environment Protection Committee of IMO in 2018, which presented candidate short-, mid- and long-term future measures to reduce GHG emissions and set out the reduction goals (i.e., reducing carbon intensity of international shipping by at least 40% by 2030, towards 70% by 2050; and reducing the total annual GHG emissions by at least 50% by 2050, compared to 2008) (IMO, 2018). However, Van Leeuwen and Monios (2022) argue that the IMO's goals are still not ambitious and propose a much bolder policy target of full decarbonization (i.e., zero carbon emissions) and a complete ban on fossil fuel use in shipping domain by 2050. The business-as-usual institutional logic is competing with the logic of sustainability, which to a great extent constrains the introduction of stricter environmental legislation at the IMO level (Monios and Ng, 2021). According to Herdzik (2021), there are only five main specific mandatory measures adopted by the IMO with the aim of addressing shipping GHG emissions, namely, regulations on Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), Carbon Intensity Indicator (CII), Data Collecting System (DCS) and Ship Energy Efficiency Management Plan (SEEMP). Although these regulations targeting shipping emissions generally are benefit for the reduction of GHG emissions from ships, they still may have some limitations in certain cases. For example, the EEDI regulation would even lead to a slight increase in CO_2 emissions by large crude oil carriers when operating on higher revolutions-per-minute engines (Wan et al., 2018). Psaraftis (2021) points out that CII reductions would greatly depend on which assessment metric is used, supply-based metric (i.e., Annual Efficiency Ratio) or demand-based metric (i.e., Energy Efficiency Operational Indicator).

In addition to the IMO's shipping decarbonization policies, there are various regional and national regulatory policy frameworks that aim at reducing shipping GHG emissions (Alamoush et al., 2022). For instance, the EU has introduced the Monitoring, Reporting and Verification (MRV) regulation to measure the GHG emissions from ships in EU ports (Gritsenko, 2017). Recently, the European Commission has launched its "Fit for 55" package of proposals with the aim of reducing the EU's total GHG emissions by 55% by 2030, paving the way for climate neutrality in the Union by 2050. As a result, the shipping industry is facing more stringent EU regulations including the European Trading System Directive, FuelEU Maritime Regulation, Alternative Fuels Infrastructure Regulation and Energy Taxation Directive (DNV GL, 2021). California Air Resources Board (CARB) has set up regulations to reduce emissions from ocean-going vessels since the 2000s (Port of Los Angeles, 2021). In China, a number of non-binding policies in a guiding nature have been issued to promote shipping emissions reduction from various aspects, but specific binding policies with controlling functions are still lacking from the technical perspective (Li W. et al., 2021). Regarding the methods that are used to analyze shipping decarbonization policies, it is worth mentioning that the overwhelming majority of the existing relevant literature adopt qualitative approaches, only few studies conducts quantitative analysis (e.g., Dirzka and Acciaro, 2021; Lindstad et al., 2022).

2.2 Policy evaluation

Policy evaluation is mainly about the assessment of the effects of a policy under certain assumptions (Brock et al., 2007). A scientific and reasonable policy evaluation analysis can effectively help policymakers further adjust and improve their policies (Zhang et al., 2022). Choosing an appropriate method is critical for the policy evaluation. In the policy evaluation literature, scholars have proposed many qualitative and quantitative methods to evaluate policy effects (Peterman, 2011). Compared with the qualitative methods for policy evaluation (e.g., case study, expert interview, conceptual framework), quantitative methods such as difference-in-difference (DID) model and regression discontinuity (RD) approach dealing with typical statistical data or atypical data have attracted more attention because of the revival of quantitative positivism (Albaek, 1989; Tang, 2007). For example, Liu et al. (2022) adopt the DID model to measure the policy effects of air pollution control policies in the Jing-Jin-Ji region, and find that those policies can reduce air pollution overall but not emission of every pollutant. Zhang et al. (2020) demonstrate that there exists a causal relationship between the sulfur dioxide emission reduction and the implementation of emission control area policy in Shanghai Port by using the RD method. It is noticeable that these commonly used policy evaluation methods actually have their deficiencies to some extent (Li and Guo, 2022). Take the DID method as an example, several assumptions such as the existence of parallel trends and stable unite treatment value assumption are supposed to hold when using the DID to detect a mean causal policy effect (Lee and Lemieux, 2010).

Unlike those policy evaluation methods focusing on the detection of policy effects, the PMC-Index model, as a quantitative method, not only provides evaluation for a single policy but also enables the consistency comparison among different policies by considering various policy elements based on the policy contents (Estrada, 2011; Kuang et al., 2020; Tian et al., 2022). Due to the significant comprehensiveness and operability, the PMC-Index model has been widely introduced into the domain of policy evaluation. For instance, Yang et al. (2021) use the PMC-Index method to evaluate the Chinese new-energy vehicle industry policies in the context of technical innovation, and find out that those policies are generally reasonable and well designed. Liu and Zhao (2022) evaluate 126 textile industry policies issued from 2014 to 2020 in China, and point out that the policy nature is relatively single and the incentive guarantee needs further improvement. In addition to the quantitative evaluation, the PMC-Index approach can also visualize the policy strengths and weaknesses by constructing the PMC surfaces according to the results of the PMC index matrix (Lu et al., 2022; Wang et al., 2022).

3 Method and data collection

3.1 PMC-Index model

As a newly developed method for policy evaluation, the PMC-Index model is proposed by Estrada (2011) based on the "Omnia Mobilis" assumption to provide quantitative evaluation of relevant policies and their strengths and weaknesses. Unlike the "Ceteris Paribus" assumption that is often applied to policy evaluation in early studies, the "Omnia Mobilis" assumption holds that everything is dynamic and interconnected, and no important relevant variables should be ignored or belittled when building a policy evaluation model (Estrada and Yap, 2013). Therefore, the PMC-Index model focuses on policy consistency assessment by considering important relevant variables as many as possible from various perspectives (Estrada, 2011; Kuang et al., 2020; Li and Guo, 2022).

There are four basic steps to apply the PMC-Index model. Specifically, (I) Classification of variables. An indicator system for policy evaluation is built, which includes main-variables and corresponding sub-variables. Indicators are generally set with the aim of reflecting key policy elements, such as policy makers, policy types and policy topics. (II) Identification of parameters and establishment of a multi-input-output table. Due to the qualitative nature of evaluation indicators, the parameters of specific sub-variables are set in binary (i.e., 0 and 1) according to the full policy text reading and in-depth analysis. If a sub-variable fits into the policy modeling, its parameter is set to 1, otherwise the parameter is set to 0 (Estrada, 2011). A multi-input-output table is constructed to present the value of parameters of all sub-variables. (III) Calculation of the PMC index. The value of the PMC index equals to the sum of all main-variables. Thus, the PMC index is measured as:

$$\mathrm{PMC} = \sum_{i=1}^{m}(X_i[\sum_{j=1}^{n}\frac{X_{ij}}{T_i(X_{ij})}]) \tag{1}$$

where X_i is the value of the main-variable i. $X_{i,j}$ denotes the value of the sub-variable j that belongs to the main-variable i . $T_i(X_{i,j})$indicates the total number of sub-variables of the main-variable i . (IV) Construction of the PMC surface. The surface is used to graphically show the results of the PMC index matrix, which can help better understand policy consistency from a visual multi-dimensional perspective.

3.2 Data collection

To effectively sort out the authoritative China's shipping decarbonization policies, we adopt a three-step approach to form our research database. Firstly, we set down eligibility criteria according to our research focus: (i) only national shipping-related or transportation-related policies issued by the State Council and the Ministry of Transport are considered. Here it is worth clarifying that the reason why we focus on the relevant policies of the State Council and the Ministry of Transport is because these two policy-makers represent the central government and its specialized transport management department, respectively. Thus, they are authoritative national administrative organizations in the transport sector; (ii) all or parts of the contents of the selected policies should be closely related to the topic of shipping decarbonization; (iii) the policies should be issued within the past decade from January 2012 to June 2022. Secondly, we search the relevant policies on the websites of the State Council and the Ministry of Transport by using the above-mentioned eligibility criteria. Thirdly, a collective discussion is organized among the authors after the full reading of the selected policies to refine our policy collection. We finally collect the 15 representative policies (see Table 1) that are dealing with shipping decarbonization affairs to different extents as our research database. Note that among these 15 policies, there are two policies P_7 and P_9 (i.e., "*Guiding Opinions on Promoting the Development of Green Shipping in the Yangtze River Economic Belt*" and "*Action Plan for Promoting Green Development of Pearl River Water Transport (2018-2020)*") focusing on the regional rather than national river waters. Notwithstanding, there two policies can be still considered as national policy representatives because the Yangtze River and Pearl River are the two most important navigable inland waters in China with massive shipping activities and large affected areas.

4 PMC-Index model construction for shipping decarbonization policies

In this section, the PMC-Index model is constructed for China's representative shipping decarbonization policies based on the four basic steps, namely, classification of policy variables, identification of parameters and establishment of a multi-input-output table, calculation of the PMC index, and construction of the PMC surface.

4.1 Classification of policy variables

Building a system of policy variables for quantitative evaluation is critical to the construction of the PMC-Index model (Estrada, 2011). Based on the existing literature on policy evaluation, such as Yang et al. (2021) and Wang et al. (2022), and the contents of China's shipping decarbonization policies, 9 main-variables and 38 sub-variables are proposed for the constructed PMC-Index model. Each main-variable is formed by several corresponding sub-variables. Moreover, different main-variables aim to mirror various key policy elements of shipping decarbonization policies through its sub-variables. Concretely, the main-variable "Policy nature (X_1)" focuses on the general functions (e.g., prediction, supervision, suggestion) of the studied policies; "Policy timeliness (X_2)" concentrates on the length of policy implementation period (e.g., long term over ten years, medium term between 5-10 years, short term less than 5 years); "Policy issuing agency (X_3)" is about

TABLE 1 China's representative policies related to shipping decarbonization since 2012.

Item	Policy name	Policy issuing agency	Year
P_1	The 12th Five-year Plan for Energy Conservation and Emission Reduction of Highway and Waterway Transportation	Ministry of Transport	2012
P_2	Guiding Opinions on Accelerating the Development of Green Circular and Low-carbon Transportation	Ministry of Transport	2013
P_3	Guiding Opinions on Promoting Port Transformation and Upgrading	Ministry of Transport	2014
P_4	Several Opinions on Promoting the Healthy Development of the Maritime Shipping Industry	State Council	2014
P_5	The 13th Five-year Plan for Water Transport Development	Ministry of Transport	2016
P_6	The 13th Five-year Development Plan for Energy Conservation and Environmental Protection in Transportation	Ministry of Transport	2016
P_7	Guiding Opinions on Promoting the Development of Green Shipping in the Yangtze River Economic Belt	Ministry of Transport	2017
P_8	Opinions on Comprehensively and Deeply Promoting the Development of Green Transportation	Ministry of Transport	2017
P_9	Action Plan for Promoting Green Development of Pearl River Water Transport (2018-2020)	Ministry of Transport, Provincial Governments of Guangdong, Guangxi, Guizhou and Yunnan	2018
P_{10}	Guiding Opinions on Building World-class Ports Ministry of Transport, and other eight national ministries and commission	Ministry of Transport, and other eight national ministries and commissions[1]	2019
P_{11}	Guiding Opinions on Vigorously Promoting the High Quality Development of the Maritime Shipping Industry	Ministry of Transport, and other six national ministries and commissions[2]	2020
P_{12}	National Carbon Peak Action Plan by 2030	State Council	2021
P_{13}	The 14th Five-year Development Plan for Green Transportation	Ministry of Transport	2021
P_{14}	The 14th Five-year Development Plan for Waterway Transportation	Ministry of Transport	2022
P_{15}	Implementation Opinions on "Opinions of the CPC Central Committee and the State Council on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job of Carbon Peak and Carbon Neutralization"	Ministry of Transport, National Railway Administration, Civil Aviation Administration of China, State Post Bureau	2022

[1]They are National Development and Reform Commission, Ministry of Finance, Ministry of Natural Resources, Ministry of Ecological Environment, Ministry of Emergency Management, General Administration of Customs, General Administration of Market Supervision and Administration, and China National Railway Corporation.
[2]They are National Development and Reform Commission, Ministry of Industry and Information Technology, Ministry of Finance, Ministry of Commerce, General Administration of Customs, State Administration of Taxation.

the identities of policy-makers, which to a great extent determines the policy authority; “Policy type (X_4)” is closely related to the policy classification (e.g., development planning, policy guidance, implementation program); “Policy topic (X_5)” denotes the specific policy subjects, which include “shipping”, “port” and “multimodal transportation” in the current paper; “Policy preliminary assessment (X_6)” places attention on whether there exist clear objectives, comprehensive contents and adequate bases; “Policy area (X_7)” refers to the broader sectors (e.g., economic field, technological domain) beyond transportation that relevant policy measures belong to from a macro-perspective; “Policy focus (X_8)” manifests the pertinent policy measures that are taken within the scopes of policy topics with the aim of achieving policy objectives; “Policy guarantee (X_9)” emphasizes on the supporting measures (e.g., financial backing, policy propaganda, personnel training) that are taken to ensure the achievement of policy goals. It is worth mentioning that the personnel training within the scope of policy guarantee actually means the foster of talents specialized in green shipping development in the current study. Table 2 presents the main-variables and the corresponding sub-variables that are set for the evaluation of China’s shipping decarbonization policies.

4.2 Parameters identification for policy variables

As mentioned in Section 3.1, two parameters (i.e., 0 and 1) are adopted in the construction of the PMC-Index model for sub-variables. Specifically, we analyze the texts of our studied policies and have a collective discussion to determine whether the meanings of sub-variables are clearly conveyed by the contents of policies. For a particular policy, if the text of the policy keeps in line with the meaning that a sub-variable represents, then the parameter of this sub-variable is set to 1. On the contrary, if the policy is analyzed and identified to be irrelevant with a sub-variable, then the value of this sub-variable is 0. Table 3 as a multi-input-output table fully shows the parameters of sub-variables for each studied policy, from which we can easily figure out the different and same policy points covered by those studied China’s shipping decarbonization policies. Notably, the identification of these parameters provides the important basis for calculation of PMC indexes of relevant policies.

4.3 PMC index calculation results

According to the identified parameters of sub-variables that are presented in the multi-input-output table (see Table 3), the PMC index of each policy is calculated based on the formula (1) proposed in Section 3.1. Table 4 shows the results of PMC index calculation for China’s shipping decarbonization policies. To effectively evaluate the policy consistency, the evaluation criteria based on the PMC index scores are often adopted (Estrada, 2011). Table 5 presents the commonly used evaluation criteria in PMC-Index studies (e.g., Kuang et al., 2020; Yang et al., 2021).

In general, there exists an overall good policy consistency of China’s shipping decarbonization policies because the average PMC index scores 6.26. Specifically, 12 policies are evaluated as having good consistency with PMC index scores between 6 and 7.99, while 3 policies are evaluated as only having acceptable consistency with PMC index scores between 4 and 5.99. Notably, no policy is identified with low consistency or perfect consistency. The policy P_8, namely “*Opinions on Comprehensively and Deeply Promoting the Development of Green Transportation*” issued by the Ministry of Transport, gains the highest PMC index with a score of 6.71, which to a great extent shows that this policy has taken comprehensive policy elements into the consideration. Comparatively, the policy P_{15}, namely “*Implementation Opinions on ‘Opinions of the CPC Central Committee and the State Council on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job of Carbon Peak and Carbon Neutralization’*” promulgated by Ministry of Transport, National Railway Administration, Civil Aviation Administration, and State Post Bureau, scores the lowest. Although P_{15} is still classified into the acceptable level regarding the policy consistency, it can further improve its consistency from the perspective of policy completeness.

4.4 PMC surface construction

The PMC surface can graphically display the components of the PMC index *via* a stereo image, which is very useful to manifest the strengths and weaknesses of each policy (Lu et al., 2022). Due to the fact that nine main-variables are selected in the current study, a 3×3 PMC matrix can be established for each policy consequently. The value of the PMC matrix that is used to construct PMC surface can be measured as:

$$\text{PMC surface} = \begin{bmatrix} X_1 & X_2 & X_3 \\ X_4 & X_5 & X_6 \\ X_7 & X_8 & X_9 \end{bmatrix} \tag{2}$$

Figure 1 presents the PMC surfaces for China’s representative shipping decarbonization policies, respectively. The depression degrees of the PMC surface can intuitively show the policy strengths and weaknesses. In particular, the convex parts indicate that high scores have been achieved in some policy aspects, while the concave parts mean that low scores have been gained (Kuang et al., 2020). For different policies, the closer the values of the main-variables in the PMC matrix are, the more similar their PMC surfaces will be. According to Figure 1, it is not hard to see that all studied policies actually have certain aspects to be further improved. More specifically, the strengths of China’s shipping decarbonization policies are mainly reflected in following three points. First, the policy areas and foci are quite comprehensive. For instance, policy foci generally cover the mainstream methods in the domain of shipping decarbonization such as clean energy applications. Second, almost each policy has its clear policy objectives for different development stages, which implicitly means China aims to achieve its decarbonization goals in a progressive manner rather than a radical way. Third, various measures like financial support, policy supervision and institution building are taken as important tools to guarantee the smooth implementation of relevant policies. Compared to these policy strengths, the weaknesses

TABLE 2 Variables setting for evaluation of China's shipping decarbonization policies.

Main-variables	Sub-variables	Evaluation criteria for sub-variables	References
Policy nature (X_1)	Prediction ($X_{1:1}$)	Whether the nature of policy is predictive.	Estrada, 2011; Li and Guo, 2022; Liu and Zhao, 2022
	Regulation ($X_{1:2}$)	Whether the nature of policy is regulative.	
	Suggestion ($X_{1:3}$)	Whether the nature of policy is recommendation-oriented.	
	Diagnosis ($X_{1:4}$)	Whether the nature of policy is diagnostic.	
	Decision ($X_{1:5}$)	Whether the nature of policy is compulsory.	
Policy timeliness (X_2)	Short term ($X_{2:1}$)	Whether the policy will last less than five years.	Kuang et al., 2020; Yang et al., 2021; Wang et al., 2022
	Medium term ($X_{2:2}$)	Whether the policy will last more than five years, but less than ten years.	
	Long term ($X_{2:3}$)	Whether the policy will last more than ten years.	
Policy issuing agency (X_3)	State Council ($X_{3:1}$)	Whether the policy issuing agency involves the State Council.	Li and Guo, 2022; Lu et al., 2022
	Ministry of Transport ($X_{3:2}$)	Whether the policy issuing agency involves the Ministry of Transport.	
	National Development and Reform Commission ($X_{3:3}$)	Whether the policy issuing agency involves the National Development and Reform Commission.	
	Others ($X_{3:4}$)	Whether the policy involves any other issuing agencies.	
Policy type (X_4)	Development planning ($X_{4:1}$)	Whether the policy can be categorized as a development planning.	Kuang et al., 2020; Tian et al., 2022
	Guidance ($X_{4:2}$)	Whether the policy can be categorized as a policy guidance.	
	Action program ($X_{4:3}$)	Whether the policy can be categorized as an action program.	
Policy topic (X_5)	Shipping ($X_{5:1}$)	Whether the policy covers the topic of shipping.	Li Y. et al., 2021; Liu and Zhao, 2022
	Port ($X_{5:2}$)	Whether the policy covers the topic of port.	
	Comprehensive transportation ($X_{5:3}$)	Whether the policy covers the topic of comprehensive transportation.	
Policy preliminary assessment (X_6)	Clear objectives ($X_{6:1}$)	Whether the policy has clear policy objectives.	Li and Guo, 2022; Wang et al., 2022
	Comprehensive content ($X_{6:2}$)	Whether the policy has comprehensive contents.	
	Adequate basis ($X_{6:3}$)	Whether the policy has an adequate theoretical and practical basis.	
Policy area (X_7)	Economy ($X_{7:1}$)	Whether the policy can be classified into the economic field.	Yang et al., 2021; Wang et al., 2022
	Technology ($X_{7:2}$)	Whether the policy can be classified into the technical field.	
	Environment ($X_{7:3}$)	Whether the policy can be classified into the environmental field.	
	Administration ($X_{7:4}$)	Whether the policy can be classified into the administrative field.	
	International communication ($X_{7:5}$)	Whether the policy can be classified into the international communication field.	
Policy focus (X_8)	Prevention and control of pollution ($X_{8:1}$)	Whether the policy pays attention to the prevention and control of pollution.	Dai et al., 2022; Tian et al., 2022
	Green shipping governance ($X_{8:2}$)	Whether the policy pays attention to improving the governance of green shipping.	
	Optimization of transportation structure ($X_{8:3}$)	Whether the policy pays attention to adjusting and optimizing the transportation structure.	
	Clean energy applications ($X_{8:4}$)	Whether the policy pays attention to the applications of clean energy.	
	Innovation and application of low-carbon technologies ($X_{8:5}$)	Whether the policy pays attention to the use of various low-carbon technologies.	

(Continued)

TABLE 2 Continued

Main-variables	Sub-variables	Evaluation criteria for sub-variables	References
Policy guarantee (X_9)	Financial support ($X_{9:1}$)	Whether the guarantee measures of the policy involve financial supports.	Kuang et al., 2020; Li and Guo, 2022; Lu et al., 2022
	Institution building ($X_{9:2}$)	Whether the guarantee measures of the policy involve institution building.	
	Policy advocacy ($X_{9:3}$)	Whether the guarantee measures of the policy involve policy advocacy.	
	Policy publicity ($X_{9:4}$)	Whether the guarantee measures of the policy involve policy publicity.	
	Policy supervision ($X_{9:5}$)	Whether the guarantee measures of the policy involve policy supervision.	
	Organizational leadership ($X_{9:6}$)	Whether the guarantee measures of the policy involve organizational leadership.	
	Personnel training ($X_{9:7}$)	Whether the guarantee measures of the policy involve personnel training.	

of the studied policies are also relatively obvious by reflecting in three aspects. First, most policies are labeled as development plans or guidance without binding force, the non-mandatory nature to a certain extent erodes the effectiveness of these shipping decarbonization policies. Second, many policies don't pay enough attention to the diagnosis of the current policy situations, which actually are important bases for newly issued policies. Third, personnel training is often neglected by many policies. In practical terms, extensive training for shipping practitioners are very useful for the popularization of the notion of shipping decarbonization.

5 Discussion: China's shipping decarbonization policy beyond the PMC index

The above-mentioned analysis based on the PMC-Index model makes it clear that China's shipping decarbonization policies have an overall good policy consistency with consideration of various policy elements. In addition to the quantitative analysis, we conduct more discussions on China's shipping decarbonization policies by focusing on their apparent characteristics in this section. Reviewing these representative policies in our data collection reveals that more emphasis has been placed by the Chinese government on the development and application of clean energy, coordination between shipping and port industries, and governance mechanism for shipping decarbonisation issues.

5.1 Development and application of clean energy

Currently, traditional fossil fuels such as heavy fuel oil and marine diesel oil provide power for the almost entire shipping transportation (Van Leeuwen and Monios, 2022), although the IMO has introduced a regulation to limit Sulphur in ships' fuel oil to a maximum 0.5% since 2020. Driven by ambitious GHG reduction targets proposed by relevant international organizations and giant shipping companies, the transition towards alternative clean energy has been widely recognized by both academic and industrial professionals (e.g., Peter et al., 2014; Ampah et al., 2021; World Bank, 2021; DNV GL, 2022; Kouzelis et al., 2022). In China, the government is also fully aware of the importance of the clean energy transition in the shipping domain, and emphasizes the development and utilization of clean energy for ship and port operations.

In the early 2010s, the Chinese government mainly focused on the improvement of energy efficiency and took it as a crucial measure to reduce GHG emissions. For instance, the policy P_2, namely "*Guiding Opinions on Accelerating the Development of Green Circular and Low-carbon Transportation*" issued in 2013, even proposed to formulate relevant regulations on energy conservation in transportation industry. The development and use of renewable energy were only slightly mentioned then. However, in recent years, great attention has been paid to energy transition by the Chinese government, particularly after China declared its "double-carbon" strategy (i.e., China plans to reach peak carbon use by 2030 and become carbon neutral by 2060) in 2020. Although energy saving is still considered as a key path toward GHG reduction because of the status quo of energy use in China, Chinese energy strategy has gradually shifted from energy saving to the dual focuses on energy conservation and transition. The strategical role of energy transition has been adequately recognized. Therefore, alternative clean-energy-powered ships and port equipment are significantly encouraged to be developed and deployed. Take the policy P_{13} (i.e., "*The 14th Five-year Development Plan for Green Transportation*") as an example, it clearly advocates the actions to explore the application of hybrid electric, hydrogen fueled, ammonia fueled and methanol powered ships.

5.2 Coordination between shipping and port industries

Compared to the shipping decarbonization, the decarnomization of the port sector has been given relatively less attention to nowadays.

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TABLE 3 The multi-input-output table for studied China's shipping decarbonization policies.

Main-variables	Sub-variables	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}
X_1	$X_{1:1}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	$X_{1:2}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{1:3}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{1:4}$	1	0	0	0	1	1	0	0	0	0	0	0	1	1	0
	$X_{1:5}$	1	1	1	0	0	1	1	0	1	0	0	1	0	1	0
X_2	$X_{2:1}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{2:2}$	0	1	1	1	0	0	0	1	0	1	1	1	0	0	1
	$X_{2:3}$	0	0	0	0	0	0	0	1	0	1	1	0	0	0	1
X_3	$X_{3:1}$	0	0	0	1	0	0	0	0	0	0	0	1	0	0	0
	$X_{3:2}$	1	1	1	0	1	1	1	1	1	1	1	0	1	1	1
	$X_{3:3}$	0	0	0	0	0	0	0	0	0	1	1	0	0	0	0
	$X_{3:4}$	0	0	0	0	0	0	0	0	1	1	1	0	0	0	1
X_4	$X_{4:1}$	1	0	0	0	1	1	0	0	0	0	0	0	1	1	0
	$X_{4:2}$	0	1	1	1	0	0	1	1	0	1	1	0	0	0	1
	$X_{4:3}$	0	0	0	0	0	0	0	0	1	0	0	1	0	0	0
X_5	$X_{5:1}$	1	1	0	1	1	1	1	1	1	0	1	1	1	1	1
	$X_{5:2}$	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0
	$X_{5:3}$	0	1	1	1	0	1	1	1	1	1	0	1	1	0	1
X_6	$X_{6:1}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0
	$X_{6:2}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{6:3}$	1	0	0	0	1	1	0	0	0	0	0	0	1	1	0
X_7	$X_{7:1}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{7:2}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{7:3}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{7:4}$	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0
	$X_{7:5}$	1	1	1	1	1	0	0	1	0	1	1	1	1	1	1
X_8	$X_{8:1}$	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0
	$X_{8:2}$	1	1	1	0	1	1	1	1	1	0	1	1	1	0	0
	$X_{8:3}$	0	1	1	1	0	1	1	1	1	1	0	1	1	0	1
	$X_{8:4}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{8:5}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
X_9	$X_{9:1}$	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1
	$X_{9:2}$	1	0	1	1	1	1	1	1	1	0	1	1	1	1	0
	$X_{9:3}$	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1
	$X_{9:4}$	1	1	1	0	0	1	1	1	1	1	1	1	1	0	1
	$X_{9:5}$	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{9:6}$	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1
	$X_{9:7}$	1	1	0	1	0	1	0	0	0	1	1	1	0	0	0

TABLE 4 The PMC index for studied China's shipping decarbonization policies.

Main-variables	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9	P_{10}	P_{11}	P_{12}	P_{13}	P_{14}	P_{15}	Average
X_1	1	0.8	0.8	0.6	0.8	1	0.8	0.6	0.8	0.6	0.6	0.8	0.8	1	0.4	**0.76**
X_2	0.33	0.67	0.67	0.67	0.33	0.33	0.33	1	0.33	1	1	0.67	0.33	0.33	1	**0.60**
X_3	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.25	0.5	0.75	0.75	0.25	0.25	0.25	0.5	**0.35**
X_4	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	0.33	**0.33**
X_5	0.67	1	0.67	1	0.67	1	1	1	1	0.67	0.67	0.67	1	0.67	0.67	**0.82**
X_6	1	0.67	0.67	0.67	1	1	0.67	0.67	0.67	0.67	0.67	0.67	1	1	0.33	**0.76**
X_7	1	1	0.8	1	1	0.8	0.8	1	0.8	1	1	1	1	1	0.8	**0.93**
X_8	0.8	1	1	0.8	0.8	1	1	1	1	0.8	0.8	0.8	1	0.6	0.6	**0.87**
X_9	0.86	0.86	0.86	0.86	0.71	0.86	0.86	0.86	0.86	0.86	0.86	1	0.86	0.71	0.71	**0.84**
PMC index	**6.24**	**6.58**	**6.05**	**6.18**	**5.89**	**6.57**	**6.04**	**6.71**	**6.29**	**6.68**	**6.68**	**6.19**	**6.57**	**5.89**	**5.34**	**6.26**

TABLE 5 Evaluation criteria for policy consistency based on PMC index scores.

PMC index	0-3.99	4-5.99	6-7.99	8-9
Evaluation	Low consistency	Acceptable consistency	Good consistency	Perfect consistency

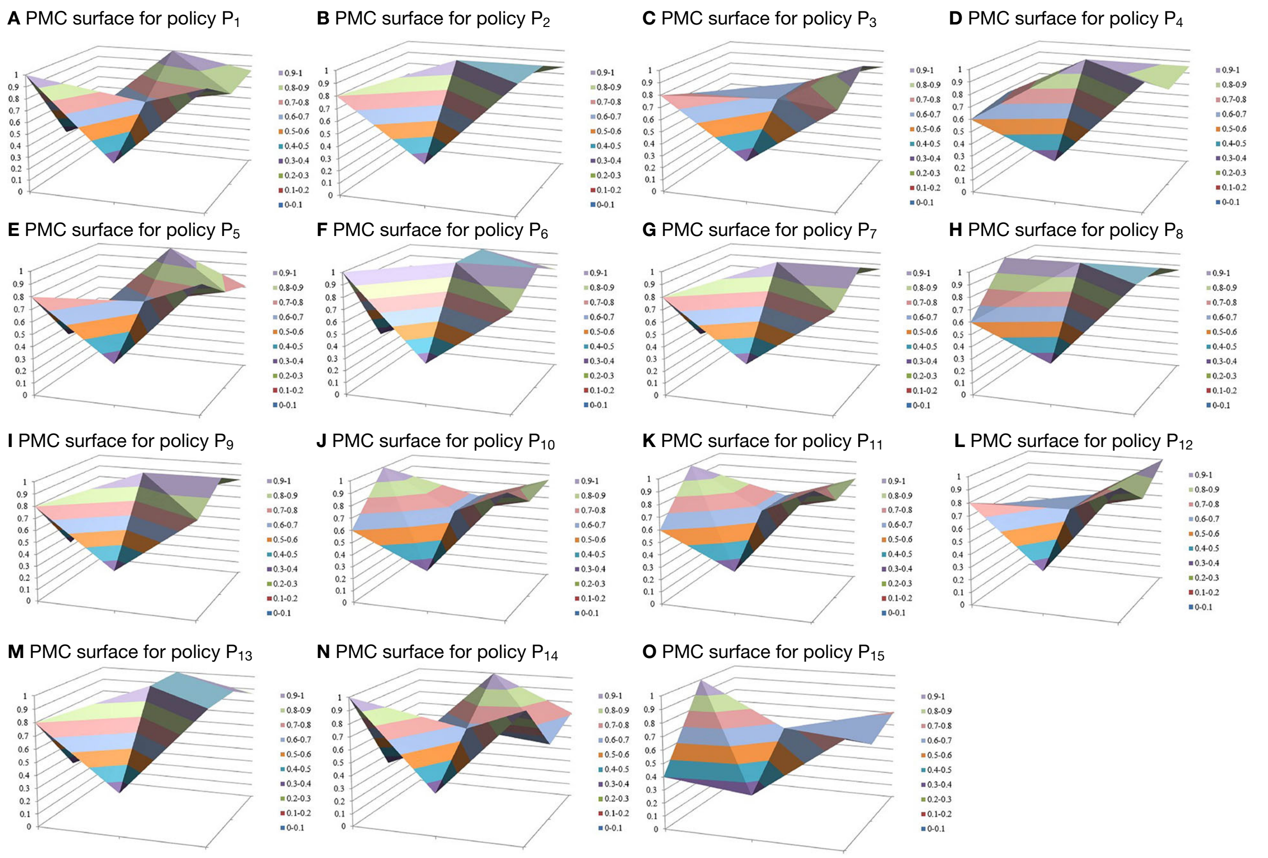

FIGURE 1
PMC surfaces for China's shipping decarbonization policies. **(A)** PMC surface for policy P_1. **(B)** PMC surface for policy P_2. **(C)** PMC surface for policy P_3. **(D)** PMC surface for policy P_4. **(E)** PMC surface for policy P_5. **(F)** PMC surface for policy P_6. **(G)** PMC surface for policy P_7. **(H)** PMC surface for policy P_8. **(I)** PMC surface for policy P_9. **(J)** PMC surface for policy P_{10}. **(K)** PMC surface for policy P_{11}. **(L)** PMC surface for policy P_{12}. **(M)** PMC surface for policy P_{13}. **(N)** PMC surface for policy P_{14}. **(O)** PMC surface for policy P_{15}.

However, ports actually play an indispensable role in maritime decarbonization especially at the ship-port interface, due to the fact that both maritime transportation and port operation are important components of maritime supply chain (Alamoush et al., 2022). In this sense, the coordination between shipping and port industries are very critical to both shipping and port decarbonization. Regarding the ways to reduce GHG emissions at the ship-port interface, there are a number of technical and operational measures such as the use of shore power, automated mooring systems and facilitation of virtual arrival (Alamoush et al., 2020). Among these measures, shore power usage has been greatly promoted by the Chinese government not only because it not only contributes to the decarbonization but also helps to reduce ship-source air pollutant emissions (Yin et al., 2020), but also due to the fact that the commercial applications of shore power equipment are still in the infancy currently (Chen et al., 2021).

Considering that the use of shore power needs the close cooperation between shipping companies and port operators, the Chinese government emphasizes the effective coordination among relevant stakeholders. According to the policy P_{10} (i.e., "*Guiding Opinions on Building World-class Ports*"), collaborative actions are encouraged to improve the utilization rate of shore power for berthing ships, and the shore power usage is chosen as an indicator to evaluate port operational performance. Moreover, the policy P_{11} (i.e., "*Guiding Opinions on Vigorously Promoting the High Quality Development of the Maritime Shipping Industry*") calls on shipping companies to install receiving facilities of shore power for their ships and use shore power during the period of ship berthing. It is worth mentioning that the policy P_{11} further suggests improving the utilization rate of shore power for international seagoing vessels by making full use of the bilateral and multilateral international maritime cooperation mechanisms. Beyond the studied representative policies in this paper, there actually exist several specialized policies on the application of shore power issued by the Ministry of Transport such as "*Port and Ship Shore Power Management Measures*".

5.3 Governance mechanism for shipping decarbonization issues

A sound environmental governance mechanism of maritime transport is critical for dealing with the issue of GHG emissions from ships (Chen et al., 2019; Monios and Ng, 2021). Although IMO has taken various governance measures to promote the process of shipping decarbonization at the global level, constructive actions at the regional level are also needed to address GHG mitigation issues (Wan et al., 2018). In recent years, the Chinese government has placed more emphasis on the establishment of governance mechanism for green transport including decarbonized shipping.

According to the policy P_{13} (i.e., "*The 14th Five-year Development Plan for Green Transportation*"), China will strengthen the construction of green traffic statistics system, and improve the data collection of energy consumption, GHG and pollutant emissions in shipping and other transportation domains, which is beneficial to the effective evaluation and supervision on decarbonization. In addition, the policy P_{14} (i.e., "*The 14th Five-year Development Plan for Waterway Transportation*") puts forward a plan to formulate technical regulations on clean-energy-powered ships with the aim of enhancing the technical standards regarding shipping decarbonization. The policy P_{15} (i.e., "*Implementation Opinions on 'Opinions of the CPC Central Committee and the State Council on Completely, Accurately and Comprehensively Implementing the New Development Concept and Doing a Good Job of Carbon Peak and Carbon Neutralization'*") highlights the role of governmental financial supports in the development of green and low-carbon transportation.

6 Conclusion and policy implications

To better understand China's shipping decarbonization policies, this study adopts the PMC-Index model to quantitatively evaluate 15 representative policies that are dealing with shipping decarbonization affairs to different extents in China. The results show that there exists an overall good policy consistency, but all studied policies have certain aspects to be further improved. In general, the existing China's shipping decarbonization policies are laying emphasis on the development and application of clean energy, coordination between shipping and port industries, and governance mechanism for shipping decarbonisation issues. According to the results of our analysis, the following two policy implications can be draw for policy-makers in China.

First, regarding the studied representative policies in this study, it is not difficult to find that nearly half of them do not merely concentrate on the shipping field but focus on the entire transportation sector with only parts of contents on green shipping issues. Therefore, it is very necessary to issue much more specialized guiding policies on shipping decarbonization such as GHG emission standards for ships, emission monitoring measures. Although China to a certain extent has built up its national macro policy system currently to accelerate the decarbonization process in the shipping domain, the relevant specific regulations are scattered in different policies without clear policy objectives or paths regarding shipping decarbonization. A specialized policy on shipping decarbonization is helpful to show the nation's ambitions for the development of green shipping, and guide the investments from industries in green shipping fuels and infrastructures. It is worth pointing out that Maritime Safety Administration of China promulgated "*Management Measures for Ships' Energy Consumption Data and Carbon Intensity*" in November 2022, which is a specialized regulation on collecting energy consumption data of Chinese ships and foreign ships using Chinese ports and determining Chinese ships' levels of carbon intensity. The implementation of abovementioned regulation is very useful to promote the shipping decarbonization from a technical management perspective.

Second, nowadays most of China's existing shipping decarbonization policies are non-mandatory lacking binding force, this is mainly because the policies formulated by the central government and its subsidiary departments are often in a guiding nature. However, in addition to those guiding policies, the Chinese central government actually has mandatory policy tools such as the formulation of regulations and laws. Compared to the non-mandatory policies, mandatory ones are more authoritative and binding. In this sense, adopting some mandatory policies perhaps is conductive to impel relevant stakeholders such as carriers, port operators to take substantial measures as quickly as possible to reduce GHG emissions. Note that supportive policies including financial incentives from governments and the establishment of carbon emissions trading system are important for shipping companies, which provides more options for them to collect funds.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material. Further inquiries can be directed to the corresponding author.

Author contributions

QZ and JZ contributed to conception and design of the study. QZ and CC organized the database. CC performed the statistical analysis. QZ and CC wrote the first draft of the manuscript. QZ, CC, JZ, and LC wrote sections of the manuscript. All authors contributed to the article and approved the submitted version.

Funding

The research is supported by the International Cooperation Project (21160710800) of Shanghai Science and Technology Committee, and Chinese National Natural Foundation Projects (42001114).

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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