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Strategic integration of data envelopment analysis and backcasting theories for zero-emission transition in global container shipping companies: pathways and frameworks

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While previous research on environmental efficiency examines data from the annual reports of shipping companies, this study takes a novel approach. It applies data envelopment analysis (DEA) and backcasting theory to assess environmental efficiency and plan the transition to cleaner fuels among global container shipping companies. Companies are categorized as first movers, second movers, and last movers based on their environmental efficiency. This categorization provides a new perspective on strategic differentiation and improvement tactics for each group. It allows for the development of strategic frameworks tailored to the unique positions of different shipping companies, aiding them achieve the International Maritime Organization's net-zero target by 2050. The study's originality lies in its use of DEA to evaluate efficiency and backcasting for strategic planning. This combination provides policymakers and industry leaders with actionable insights and a robust methodological framework for promoting sustainable maritime management. The dual approach not only contributes to academic literature, but also aids in navigating the complexities of green transitions in the shipping industry.

KEYWORDS

environmental efficiency, strategic planning, data envelopment analysis, backcasting theory, net-zero emissions

1 Introduction

Global container shipping companies (GCSCs), pivotal in the global supply chain, are striving to meet the International Maritime Organization's (IMO) commitment to sustainable shipping (Bilgili, 2021; Hellenic Shipping News Worldwide, 2021; Maersk, 2023). The IMO has developed a phased regulatory approach aimed at reducing greenhouse gas (GHG) emissions by 50% by 2050 compared with the 2008 levels (Marine Environment Protection Committee [MEPC], 2023). In response, these companies are developing strategies for the gradual introduction of carbon-neutral and eco-friendly marine fuels, supplementing existing sulfur oxides (SO_X) and nitrogen oxides (NO_X) emission regulations (Lee et al., 2024). They advocate for sustainable fuel switching through legal and institutional interventions (Lister, 2015), and are actively discussing the development and commercialization of eco-friendly marine fuel oils to reduce ship air pollution (Bilgili, 2021; Deniz and Zincir, 2016). These companies are considering eco-friendly alternative fuels such as hydrogen, ammonia, electricity, and biofuels to comply with GHG emission reduction regulations. The implementation of these regulations, led by the IMO, depends on individual company circumstances. For example, A.P. Moller - Maersk ordered a methanol-powered ship in 2022 (Maersk, 2023), while HMM established a plan to have 80% of its ships powered by eco-friendly fuels by 2050, as outlined in its '2050 Carbon Neutrality Strategy' (Hellenic Shipping News Worldwide, 2021). However, with approximately 26 years remaining until the initial IMO GHG Strategy is achieved in 2050, there is a lack of medium- to long-term direction and practical alternatives to cleaner marine fuels for the sustainability and competitiveness of these companies (Hellström et al., 2024). Recent geopolitical issues, including the US-China hegemonic rivalry in 2018, the global pandemic of 2019-2020, the Ukraine-Russia war in 2022, the Israel-Hamas war in 2023, and the Israel-Iran armed conflict in 2024, have posed challenges to meeting the IMO's 2050 carbon reduction targets (Acheampong et al., 2023). Furthermore, it is essential to comprehend how society views climate change and its dangers (Kyriakopoulos and Sebos, 2023). Consequently, in order to meet the global demand for emission reductions and ensure the sustainable development of the shipping industry, decarbonization is crucial (Xiao et al., 2025).

Global liner shipping companies are confronting escalating pressure to enhance cost competitiveness and transition to cleaner fuels. These pressure stems from both internal factors and external demands for new cargo as global supply chains restructure. In this competitive landscape, it is crucial for these companies to undertake a thorough efficiency analysis, tailored to the transition to cleaner fuels. This analysis should assess their strengths and weaknesses and evaluate their sustainable performance accordingly. This study reviews previous research on the competitiveness and environmental impact assessment of global liner shipping companies. It aims to distinguish itself by identifying and addressing gaps in previous studies, thereby proposing novel improvements. The study ultimately aims to enhance the competitiveness of shipping companies, foster environmental responsibility, and devise a comprehensive strategy for a sustainable future.

First, Data Envelopment Analysis (DEA) is a widely used tool in academic literature for assessing the managerial efficiency of shipping companies. For example, Gong et al. (2019); Lun and Marlow (2011); Mantalis et al. (2015), and Panayides et al. (2011) employed DEA to evaluate the operational efficiency of shipping companies. They found a strong correlation between ship operation costs and company revenue. Bang et al. (2012) compared the operational and financial efficiency of 14 leading global liner shipping companies in terms of tonnage. Their findings suggested that tonnage, ship size, and new building inputs positively influence the financial performance of liner shipping companies. However, vessel age and linearity insignificantly impacted operational and financial performance. Gutiérrez et al. (2014) noted that strategic alliances among major global liner shipping companies have not improved logistics efficiency and reliability amid a global supply chain crisis. Wang et al. (2021) evaluated shipping management efficiency using a congestion index approach developed through two-stage DEA. Their study underscored that the characteristics of shipping companies significantly influence efficiency. Chao et al. (2018) conducted a study to evaluate the annual efficiency of global liner shipping companies and the efficiency of different types of vessels. Their findings affirmed that optimal input sharing and fleet capacity adjustment are vital for achieving sustainable performance for shipping companies.

Second, Cariou (2011); Cariou and Cheaitou (2012); Eide et al. (2013), and Vakili et al. (2022) posit that the growth of environmental science and rising public environmental consciousness negatively affect the sustainable development of global liner shipping companies. This is because of the unregulated emissions of pollutants from ships, which impact environmental efficiency. Gong et al. (2019) compared the economic, environmental, and operational efficiency of these companies, considering ship emissions. The study employed total assets, capital expenditure, capacity, number of ships, employees, and fuel cost as input variables, and revenue, cargo, CO_2, SO_X, and NO_X as output variables. Wang et al. (2019) assessed the company's environmental efficiency from 2010 to 2015, considering undesirable outputs such as air emissions, sewage, wastewater, and solid waste. Hsieh et al. (2021) evaluated the environmental efficiency of global liner shipping companies from 2013 to 2017, focusing on shipboard air pollutant emissions. They compared the evaluation variables for each company and suggested improvements. Kuo et al. (2020) analyzed the factors affecting the efficiency of shipping operations using four inputs (employees, operating costs, owned-in fleet capacity, and chartered-in fleet capacity) and two outputs (revenue and lifting). The study demonstrated the link between the reduction of shipboard pollutant emissions and profits. Liao and Lee (2023) estimated the environmental efficiency of 11 global shipping companies from 2019 to 2021, proposing measures to reduce CO_2 emissions to achieve environmental goals. The study employed the directional distance function based on two inputs (Capacity and Fuel), one desirable output (Cargo), and one undesirable output (CO_2 emissions).

Existing literature examines the CO_2 emissions of global shipping companies. However, these studies rely solely on data from companies' annual reports, despite the fact that CO_2 emissions calculations depend on each company's constraints and considerations. Previous studies identified a lack of comprehensive academic research and practical alternatives for global liner shipping companies to promote a green shift in marine fuel oil. This shift requires decision-making that incorporates information, funding, and infrastructure investments necessary for long-term growth and to reach net-zero emissions, as outlined in the 2023 IMO strategy for the reduction of GHGs from ships. This study differs from previous research by offering practical goals and strategic plans for global liner shipping companies regarding the eco-friendly conversion of marine fuel oil. It employs backcasting theory to set a desirable future as a managerial tool, and provides practical strategic plans based on academic theory verification to achieve this goal.

This study assesses the environmental efficiency of global liner shipping companies using an undesirable output model. It proposes strategies for achieving the IMO, 2020 Net-Zero goal in the shipping industry, drawing on eco-friendly ship fuel conversion and backcasting theories. To substantiate the study's purpose, we analyzed the 2022 operating and financial reports of 20 global liner shipping companies. These companies represent over 80% of the container cargo capacity in the global shipping market. The analysis was conducted using data from the companies' official websites, Yahoo Finance statistics, and cargo capacity data from 1995 to 2022 obtained from the Clarksons Research Portal. Eight global liner shipping companies were selected as decision-making units (DMUs) to analyze their environmental efficiency. This study differs from previous ones in that it evaluates the environmental efficiency of global liner shipping companies by considering their willingness to switch to eco-friendly ship fuel. This willingness is considered an input variable tied to the company's own vessel capacity. The study also investigates the detailed specifications of each company's vessel, such as its use of eco-friendly ship fuel and eco-friendly electric engines. This allows for a more objective calculation of CO_2 emissions, ensuring the scientific verifiability and logical completeness of the study. Furthermore, this study offers policy implications for global liner shipping companies aiming to achieve the IMO 2050 Net-Zero goal. Therefore, we review the ship ordering status of global liner shipping companies up to 2027, based on data from Clarksons Research Portal and the Environmental, Social, and Governance (ESG) section of sustainability reports posted on the companies' individual websites. This information is then used to derive policy implications using backcasting theory.

The research questions are as follows. First, this study, guided by the 3W1H approach, aims to empirically investigate the strategic direction and purpose behind the eco-friendly fuel conversion of global liner shipping companies. The 3W1H approach, a structured problem-solving method that facilitates logical exploration and informed decision-making (Jabbari et al., 2023), has been widely employed in various studies (Batool et al., 2023; Gu et al., 2022; Malik et al., 2020). This study applies the 3W1H approach to understand the eco-centric objectives of global liner shipping companies, focusing on four aspects: who, why, what, and how. The "who" refers to global liner shipping companies operating the world's greenest and most efficient container ships. The "why" analyzes the reasons behind the relatively low efficiency of these companies, using high environmental efficiency companies as benchmarking targets. The "what" pertains to the 2050 full-cycle net-zero GHG emissions target for global liner shipping companies, consistent with the IMO's shipboard carbon emissions regulation. The "how" presents practical measures for these companies to meet the IMO's 2023 GHG reduction strategy, using backcasting theory. Figure 1 presents the research questions derived from the 3W1H approach

Second, Figure 2 presents the research process. Accordingly, Chapter 3 discusses the need and justification for transitioning to eco-friendly ship fuel, driven by the paradigm shift toward environmental friendliness. It also explores the rationale for proposing a different strategic direction from existing literature, using backcasting theory. This chapter describes the DEA methodology and the data to be analyzed for global liner shipping companies. Chapter 4 presents empirical results and responses to key questions, based on environmental efficiency analysis results, Slack information, future ship orders of global liner shipping companies, green targets consistent with the IMO's 2023 GHG reduction strategy, and backcasting theory. Chapter 5 discusses the policy, social, and originality/value implications of this study. Lastly, Chapter 6 summarizes the study, draws conclusions, and identifies the study's limitations and contributions.

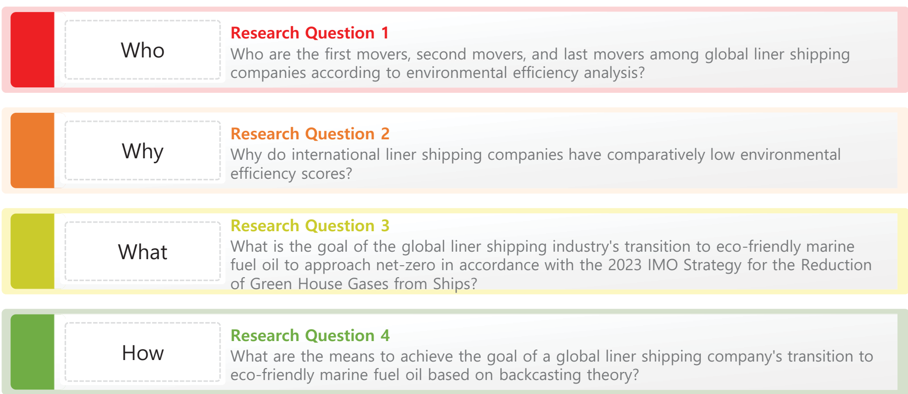

FIGURE 1
Research questions derived from 3W1H approach. Source: Author's own compilation.

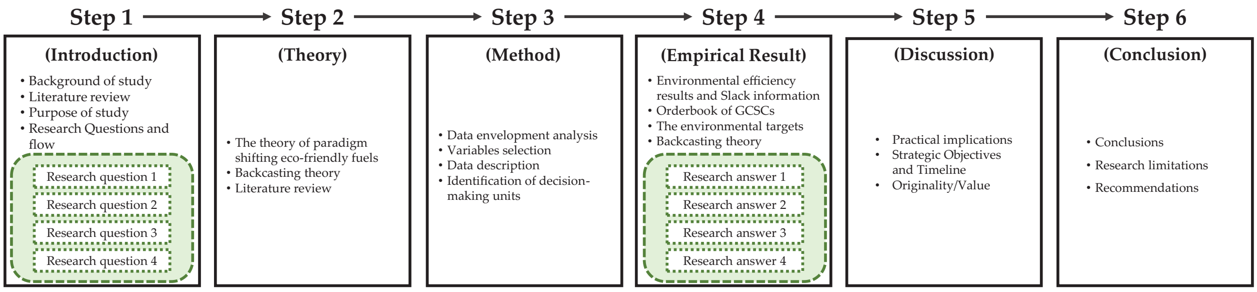

FIGURE 2
Process of research. Source: Author's own compilation.

2 Theory

2.1 Paradigm-shifting eco-friendly fuels by global container shipping companies

The global community faces a shared challenge that necessitates collective action through international or regional agreements. Transboundary air pollution contributes to global warming, extreme weather events, and other environmental issues (Manisalidis et al., 2020). Global liner shipping companies are working to implement ESG principles to meet shippers' expectations regarding environmental, socio-technical, and business risks, while also creating opportunities for a sustainable future and complying with international environmental regulations (Lee et al., 2024).

In response to the transboundary nature of ship-borne air pollution, these companies adopted the Ship Energy Efficiency Management Plan for all internationally voyaging ships at the 62nd session of the MEPC in 2011. The Committee (MEPC) approved an amendment to Annex VI of MARPOL 73/78 in 2011 to regulate GHG emissions from container ship operations (Fan et al., 2024). In March 2024, the World Shipping Council (International Chamber of Shipping), representing shipping companies, highlighted at the 81st session of the IMO's MEPC that ships engaged in international navigation vary in age. To address the practical limitations of replacing all ships simultaneously with environmentally-friendly marine fuel ships, it emphasized the importance of creating an environment where ships and energy suppliers can use a variety of fuels, energy sources, and technologies. This approach is based on a paradigm shift toward greener marine fuel through the joint implementation of pollutant emission regulations and the sequential replacement of ships.

Applying Thomas Samuel Kuhn's concept of a paradigm shift from "Structure of Scientific Revolutions" (Shapere, 1964) to the shipping industry reveals that current global liner shipping companies actively prioritize eco-friendliness, reflecting societal needs over cost reduction and profit generation to maintain sustainability. Shippers may perceive this as a symbolic representation of a standardized global liner shipping company undergoing a paradigm shift (Kovacs, 2022). Therefore, global liner shipping companies must diverge from the previous paradigm of solely pursuing commercial interests, such as containerized cargo transport and profit-making. Instead, they should focus on sustainable development and long-term economic value creation based on environmental justice theory (Li et al., 2023). Global stakeholders are urging these companies to shift toward the use of cleaner marine fuels to ensure the marine environment's sustainability for future generations. This shift should reduce the impact of ship-borne air pollution through the introduction of sustainable and environmentally-friendly marine fuel oils, efficient ship operation management, and related technologies (Wang et al., 2023). Consequently, global liner shipping companies primarily aim to operate vessels that use environmentally-friendly marine fuel oil, ensuring the sustainability of the ESG domains. This approach allows them to fulfill their environmental responsibilities, promote environmental justice in the long term, and lay the foundation for future generations.

2.2 Backcasting theory to address eco-friendly fuel adoption issues

The dialogue on the shift toward sustainable socio-technical systems has advanced given accelerated global climate change, increased use of low-carbon energy in land and maritime transport, and other aspects of the sustainability transition. Backcasting method proves effective in formulating strategies to achieve concrete objectives (Bibri, 2018). Historically, global shipping companies' transition to environmentally-friendly marine fuel oil has relied on forecasting methods. These methods focus on designing internal strategies to maintain or enhance ship operations at a low cost within the existing Bunker C framework. This approach, however, has been unable to adapt to changing circumstances and conditions. To address these limitations, this study adopts backcasting, an approach that contrasts with forecasting. Backcasting sets the green vision and goals for the future shipping industry from a long-term perspective, and then identifies the institutions, policies, and technologies necessary to realize them (Danish et al., 2024). This study, therefore, employs backcasting as a research method, which is ideal for setting growth strategy targets based on a clear future direction toward greener marine fuels in the global liner shipping industry.

Backcasting theory provides a suitable theoretical framework to solve the problem through a normative-strategic approach. This theory relies on context and empirical analysis, linking the conditions and tasks for realizing a viable global liner shipping company to the methodology of the normative model (Tuominen et al., 2014).

In conclusion, the backcasting methodology used in this study is a normative approach that pre-establishes the desired future state. It aims to align the shipping company with net-zero emissions consistent with the 2023 IMO strategy for reducing GHGs from ships. This allows global liner shipping companies to present the most effective policies to achieve a quantum leap, defined as a catch-up plan (Bibri and Krogstie, 2019). By using backcasting theory to identify strategic tasks for global liner shipping companies, it is possible to develop a concrete action plan for second and third-tier companies to reach the status of top-tier global shipping companies that have successfully transitioned to eco-friendly ship fuel.

2.3 Literature review

Previously, various studies have been conducted to understand the regulations on eco-friendly ships and the current market situation. Serra and Fancello (2020) explained that fundamental changes in fuel, technology, operations, and business practices in the shipping industry must be implemented to comply with the new IMO's regulations. Balcombe et al. (2019) explained that the path to achieving GHG reduction by 2050 is unclear, but multi-faceted responses are needed for in-depth decarbonization. He further explained that in the long run, deeper decarbonization requires strong financial incentives. Lee and Nam (2017) identified regulations on eco-friendly ships in major countries such as Europe, the United States, Japan, China, and South Korea, and explained that South Korea needs strategies such as establishing a shipping-ship cooperation network, sharing shipping-ship business information and reducing joint costs, investing in eco-friendly ship research and development, and expanding LNG fuel ship support. Halim et al. (2018) explained that international shipping companies' barriers to achieving decarbonization include sunk costs, path dependence, carbon emissions as negative externalities: the Climate as Unprecedented Public Good, Incentives, and Information Asymmetry. Ann et al. (2023) identified the impact of energy efficiency and decarbonization on Korean container ships in accordance with IMO regulations, and explained that eco-friendly technologies such as engine output limitations, energy-saving devices, and alternative marine fuels should be reviewed. Afterwards, it was explained that it is most desirable to introduce LNG fuel on Korean container ships based on the marginal abatement cost for the fleet.

Consistent with these changes, global container shipping companies are actively converting eco-friendly fuels. In March 2022, Maersk entered a strategic partnership with six companies worldwide to secure green methanol (biometall and e-methanol) on large scale by 2025. MSC further presented a plan in response to the European Green Deal to reduce CO2 emissions using alternative fuels (Grzelakowski et al., 2022). However, various studies are being conducted to analyze the economic and environmental effects of global container ships' fuel conversion according to the eco-friendly fuel conversion of global container ships. Elkafas et al. (2021) analyzed the environmental and economic benefits of replacing diesel oil with the natural gas-diesel dual fuel for container ships. The analysis was conducted on A7 container ships owned by Hapag-Lloyd, and the proposed dual fuel engine showed that carbon dioxide, nitrogen oxides, sulfur oxides, particulate matter, and carbon monoxide (CO) emissions were reduced by 20.1%, 840 $/ton, 9,864$/ton, 27,761$/ton, and 4,307$/ton cost-effectiveness, respectively. Additionally, Elkafas et al. (2022) analyzed large container ships operating on the East-West trade, and explained that dual fuel engines that operate with natural gas reduce carbon dioxide, sulfur oxides, and nitrogen oxides by 28%, 98%, and 85%, respectively, compared with diesel engines. Additionally, it was explained that when a dual fuel engine powered by methanol is used, the reduction effect reaches 7%, 95%, and 80%, respectively. Based on these results, it was argued that the use of dual fuel engines would improve the ship's energy efficiency index by 26% and 7%, respectively. Ammar (2019) conducted an environmental analysis of methanol-diesel fuel engines on cellular container ships, and explained that when using the fuel engine, nitrogen oxides, sulfur oxides, carbon monoxide, carbon dioxide, and particulate matter emissions were reduced by 76.78%, 89%, 55%, 18.13%, and 82.56%, respectively.

Considering previous studies, various technical and policy measures for reducing greenhouse gas emissions and sustainable shipping activities are being discussed, according to IMO regulations. In fact, it was confirmed that the economic and environmental effects of using alternative fuels for the zero-emission transition of global container shipping companies were evaluated. However, global shipping companies' predictions on the conversion of eco-friendly ship fuel oil mainly focus on how to maintain or improve ship operations at low costs in the existing Bunker C using forecasting method, and there is a limit to not achieving the goal according to changes in circumstances and conditions. To solve this problem, this study adopts environmental efficiency analysis through Undesirable output DEA analysis and backcasting theory to fill the gap between goal and reality, and overcome challenging limitations.

3 Method

3.1 Data envelopment analysis

The DEA model, a widely recognized tool for efficiency analysis, compares and evaluates the relative efficiency of DMUs by analyzing the weighted magnitudes of various input and output variables. DEA models are divided into two categories: the Charnes, Cooper, and Rhodes (CCR) model, which assumes Constant Returns to Scale, and the Banker, Charnes, and Cooper (BCC) model, which assumes Variable Returns to Scale. As long as the target DMUs' ratio does not surpass one and the weights of each input and output are greater than zero, the DEA-CCR model, a linear fractional programming technique, maximizes the ratio of the output-weighted sum to the input-weighted sum of the DMUs.

However, because it cannot differentiate between scale and pure technical efficiencies and assumes that the return to scale is constant, the CCR model has limitations. The estimation by the CCR model can appear inefficient, if the production technology is a variable return to scale, while it actually is an efficient DMU. Therefore, in order to overcome this, Banker et al. (1984) proposed the BCC model, which adds the convexity requirement and relaxes the restriction on the constant returns to scale, using the assumption of variable returns to scale. The DEA model can also identify scale efficiency (SE) by comparing the efficiencies of the CCR and BCC models. However, the DEA model, which evaluates organizational performance efficiency, overlooks the slack between inputs and outputs. It operates under the assumption that inputs or outputs increase or decrease proportionally, which is a limitation of the radial model derived from DEA analysis. This model fails to rank the most efficient DMUs. Furthermore, the DEA model is an oriented model with a specific direction, such as input-oriented or output-oriented, which does not provide individual efficiency information for inputs or outputs.

To address these issues, this study adopts the Slack-Based Measure of Efficiency (SBM)-DEA model, which compensates for the DEA model's limitation of calculating the efficiency value as 1 despite the inefficient state of residual variables. The SBM-DEA model, proposed by Tone (2001), not only evaluates the efficiency between DMUs using the same distance concept as the DEA model, but also considers the slack overlooked in DEA. The non-radial SBM-DEA analysis does not assume a proportional increase or decrease in inputs or outputs, and derives optimal efficiency by considering both input residuals and output shortages simultaneously. The non-oriented SBM model (SBM Non-oriented) improves inputs and outputs simultaneously, considering both radial and non-radial slacks, allowing for the optimization of inputs and outputs without a specific direction. Consequently, the SBM-DEA model, which clearly reveals rankings among DMUs (Tone, 2002), is a more reasonable efficiency evaluation method than the DEA model.

Cooper et al. (2006) proposed the undesirable output model to consider undesirable outputs in the SBM model proposed by Tone (2001). This model derives efficiency by considering undesirable outputs in addition to the inputs and outputs covered in DEA analysis. Equation 1 presents the output formula of the undesirable output model:

$$\begin{aligned} \rho = min \frac{1-\frac{1}{m}\sum_{i=1}^{m}\frac{s_i^-}{x_{io}}}{1+\frac{1}{s_1+s_2}\left(\sum_{r=1}^{s_1}\frac{s_r^g}{y_{ro}^g}+\sum_{r=1}^{s_2}\frac{s_r^b}{y_{ro}^b}\right)} \\ subject\ to\ x_o = X\lambda + s^- \\ y_o^g = Y^g\lambda - s^g \\ y_o^b = Y^b\lambda + s^b \\ s^-, s^g, s^b, \lambda \geq 0 \end{aligned} \quad (1)$$

Cooper et al. (2007) assume there are n DMUs with three variables—inputs, good outputs, and bad outputs—represented by three vectors— $x \in R^m$, $y^g \in R^{s_1}$, and $y^b \in R^{s_2}$—respectively. The matrices X, Y^g, and Y^b are then defined as follows: $X = [x_1, \cdots, x_n] \in R^{m \times n}$, $Y^g = [y_1^g, \cdots, y_n^g] \in R^{s_1 \times n}$, and $Y^b = [y_1^b, \cdots, y_n^b] \in R^{s_2 \times n}$, where $X > 0$, $Y^g > 0$, $Y^b > 0$, and $\lambda \in R^{s_1 \times n}$ is the intensity vector. The vector $s^g \in R^{s_1}$ represents shortages in good outputs, whereas the vectors $s^- \in R^m$ and $s^b \in R^{s_2}$ expresses excesses in inputs and bad outputs, respectively. In the undesirable output model, DMUs are only efficient when $\rho = 1$, $s^- = 0$, $s^g = 0$, and $s^b = 0$.

3.2 Variables selection and data description

To facilitate the scientific analysis of this study's results, it is crucial to select input and output variables based on their potential implications, as they significantly impact the DEA results. A thorough review of previous efficiency analysis studies of general shipping companies suggests that the environmental efficiency of global liner shipping companies can be estimated using various variables, including total assets, fleet size, number of ships, revenue, and pollutant emissions. The selection of variables for this study was guided by three principles to ensure their appropriateness and reliability. First, the optimal number of variables for DEA analysis was determined considering the reliability of the results, which is achieved when the number of DMUs is at least twice the sum of the input and output variables (Dyson et al., 2001; Golany and Roll, 1989; Homburg, 2001). Second, the DEA should select and analyze variables for DMUs to identify relatively inefficient variables and select those that can be improved, as the DEA is aimed at maximizing output. Third, the variables should be directly related to DMUs, and subjective judgment should be excluded. Consequently, we selected two inputs: total assets (in billion USD) and ownership (in TEU), one desirable output: turnover (in billion USD), and one undesirable output: CO_2 emissions (in million tons), based on the variables used in previous studies on the efficiency of general shipping companies. The data used for this study's analysis was obtained from Clarkson Research statistics, annual reports, financial reports, and websites of global liner shipping companies up to 2022 through a scientific data preprocessing process. Figure 3 illustrates the data collection process.

However, this study acknowledges the limitation that CO_2 emissions are calculated differently across global liner shipping companies given varying constraints and considerations, and objective CO_2 emissions data are not readily available. To address these limitations, this study derives a formula for calculating CO_2 emissions based on the Intergovernmental Panel on Climate Change (IPCC) 2006 guidelines. This formula considers factors such as fuel usage, fuel type, and emission factors, and relies on official information obtained through a review of authorized reports (IMO, 2020). In estimating the CO_2 emissions from vessels operated by global liner shipping companies, this study builds upon existing research (Czermański et al., 2021). It assumes that container vessels operate for 250 days per year at a speed of 17 knots. The emission factor per vessel, based on fuel consumption according to vessel size, is calculated using data from IMO (2020). Notably, IMO (2020) suggests that a potential reduction of CO_2 emissions by 0.25% can be achieved by improving the performance of the main engine by 2030. This implies that if a ship is equipped

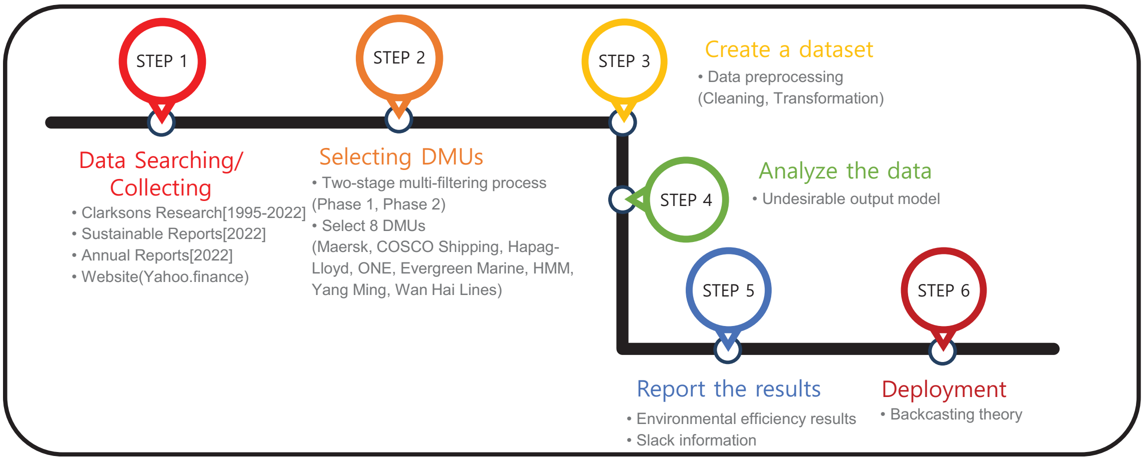

FIGURE 3
Journey through dataset analysis. Source: Author's own compilation.

with an electronically controlled main engine, the CO_2 emissions can be reduced to 99.75% of those from a conventional mechanically controlled engine. Equation 2 expresses the CO_2 emissions formula proposed in this study:

$$CO_2\ emissions = \sum_{ij}(FC_i \times EF_{ij} \times EE_i) \tag{2}$$

$$subject\ to\ FC_i, EF_{ij}, EE_i \geq 0,$$

where FC_i denotes the fuel consumption of vessel i, EF_{ij} denotes the emission factor for vessel i fuel j, and EE_i denotes the engine efficiency. Table 1 shows the sources of the variables used in the global liner shipping enterprise efficiency analysis.

Table 2 presents the inputs and outputs for the global liner shipping company DMUs.

Table 3 presents the basic statistics for the global liner shipping company DMUs' inputs and outputs.

3.3 Identification of decision-making units

This study scrutinizes the environmental efficiency of 20 major global liner shipping companies, collectively representing over 80% of container vessels, therefore ensuring a representative sample of the global shipping market based on freight space (Chao et al., 2018; Kuo et al., 2020). This focus is motivated by the ongoing efforts to expand cargo capacity related to eco-friendly marine fuel-powered vessels in a bid for self-reliance, especially given the impending abolition of the European Union's Consortia Block Exemption Regulation (CBER) on April 25, 2024 (Reed Smith, 2024). As in Table 4, the initial data processing step involved excluding MSC, CMA CGM, PIL, SITC, IRSIL, and Sinokor Merchant Marine from the DMU given the difficulty in obtaining financial information, as these are privately held shipping companies. In this study, total asset is used as input variable and Revenue is used as desired output variable in environmental efficiency analysis. Therefore, financial information on the two variables must precede before the analysis of environmental efficiency. So we had no choice but to exclude companies that did not provide financial information from the analysis.

In the second data preprocessing phase, several liner shipping companies (ZIM, X-Press feeders Group, KMTC, UniFeeder, Sea Lead shipping, Sinokor Merchant Marine, and Zhonggu Logistics Corp.) were excluded per Clarkson Research data. These companies were deemed unsuitable for comparison within the DMU given their relatively small capacity.

In this study, eight global liner shipping companies (Maersk, COSCO Shipping, Hapag-Lloyd, ONE, Evergreen Marine, HMM, Yang Ming, and Wan Hai Lines) were chosen as DMUs. Their selection followed a two-stage multiple filtering procedure (Figure 4), implemented considering specific limiting factors.

TABLE 1 The source of input and output variables.

Type	Variables	Unit	Data sources
Inputs	Total assets	Billion USD	Annual reports, Finance reports, Website
	Own Capacity	TEU	Clarkson research
Output	Revenue	Billion USD	Annual reports, Finance reports, Website
Undesirable output	CO2 emission	Million Ton	Authors' proposed formulation

Source: Authors' own compilation.

4 Empirical Results

4.1 First movers, second movers, and last movers according to the environmental efficiency

The undesirable output model analysis considers desirable and undesirable outputs to assess the effectiveness of environmental

TABLE 2 Inputs and outputs of individual decision-making units (2022).

Global shipping lines	Inputs		Desirable output	Undesirable output
	Total assets (billion USD)	Own Capacity (TEU)	Revenue (billion USD)	CO_2 emission (million Ton)
Maersk	55.27	2,398,256	48.10	16.04
COSCO Shipping	35.46	2,137,198	27.09	11.74
Hapag-Lloyd	25.16	1,068,103	22.46	6.15
ONE	28.63	868,969	16.80	5.22
Evergreen Marine	15.91	908,107	11.25	5.57
HMM	14.13	614,229	10.11	2.79
Yang Ming	5.30	258,084	3.92	2.00
Wan Hai Lines	7.86	367,851	5.57	3.49

Source: Clarkson research and financial reports from each company.

efficiency enhancements. From Table 5, the CCR model identifies Hapag-Lloyd as the most environmentally efficient among global shipping companies. The BCC model, however, ranks Maersk, Hapag-Lloyd, HMM, and Yang Ming at the top for environmental efficiency. Therefore, Hapag-Lloyd emerges as the most efficient according to the SE model. categorization of DMUs into three groups: first movers, second movers, and last movers, as depicted in Figure 5. This categorization was followed by the identification of areas for environmental efficiency improvement. The first movers group comprises leading global liner shipping companies with environmental efficiency significantly above the average. Specifically, in this study, Maersk and Hapag-Lloyd are classified as first movers, reflecting their leadership in achieving the IMO's 2050 Net-Zero commitment. First movers are those that have pioneered new sales markets to secure large global shippers' volumes and have the potential to enhance their brand image through green shipping technological innovations. Despite the potential competitive advantage in the absence of competitors, first movers face challenges such as high initial costs, risks, and uncertain market response.

The second movers group consists of global liner shipping companies with eco-efficiency comparable to the sample average, including HMM and ONE. Second movers are companies that enter the global liner shipping market following the first movers, who have already established a robust presence. They can gain a competitive edge by identifying and addressing the first movers' weaknesses. However, they may encounter high entry barriers and competition between shippers and long-established shipping companies. The last movers group includes DMUs that need substantial environmental efficiency improvements. Yang Ming, COSCO Shipping, Wan Hai Lines, and Evergreen Marine fall into this category. In this study, last movers are defined as the final entrants into the global liner shipping market after several players have already entered. They may enter the market by identifying the weaknesses of the first and second movers, and learning from their failures. However, they may still face significant competition from incumbents given the saturation of the global liner shipping market.

4.2 Why the efficiency of global container shipping companies is lower than a model company

This study investigates the reasons behind the relatively low environmental efficiency of global liner shipping companies by comparing them with first movers. The research found that high

TABLE 3 Descriptive statistics for input and output variables.

Global shipping lines	Inputs		Desirable output	Undesirable output
	Total assets (billion USD)	Own Capacity (TEU)	Revenue (billion USD)	CO_2 emission (million Ton)
Avg	23.46	1,077,599.63	18.16	6.62
Max	55.27	2,398,256.00	48.10	16.04
Min	5.30	258,084.00	3.92	2.00
Mid	20.54	888,538.00	14.02	5.40
St Dev	15.42	735,636.46	13.56	4.53

Source: Authors' own compilation.

TABLE 4 Decision-making unit selection among 20 Global container shipping lines.

Ranking	Global shipping company	Private corporation*	Under 100,000TEU Own Capacity**	DMU
1	MSC	O***	–****	–
2	Maersk	–	–	✓*****
3	CMA CGM	O	–	–
4	COSCO Shipping	–	–	✓
5	Hapag-Lloyd	–	–	✓
6	ONE	–	–	✓
7	Evergreen Marine	–	–	✓
8	HMM	–	–	✓
9	Yang Ming	–	–	✓
10	ZIM	–	O	–
11	Wan Hai Liens	–	–	✓
12	PIL	O	–	–
13	SITC	O	–	–
14	X-Press feeders Group	–	O	–
15	KMTC	–	O	–
16	IRSIL Group	O	–	–
17	UniFeeder	–	O	–
18	Sea Lead shipping	–	O	–
19	Sinokor Merchant Marine	O	O	–
20	Zhonggu Logistics Corp	–	O	–

*Annual reports (2022) and Website (Yahoo Finance).
**Clarksons Research (1995–2024).
Source: Authors' own compilation.
***O means it is included in the criteria.
****– means it isn't included in the criteria.
*****✓ represents the company has been selected as DMU.

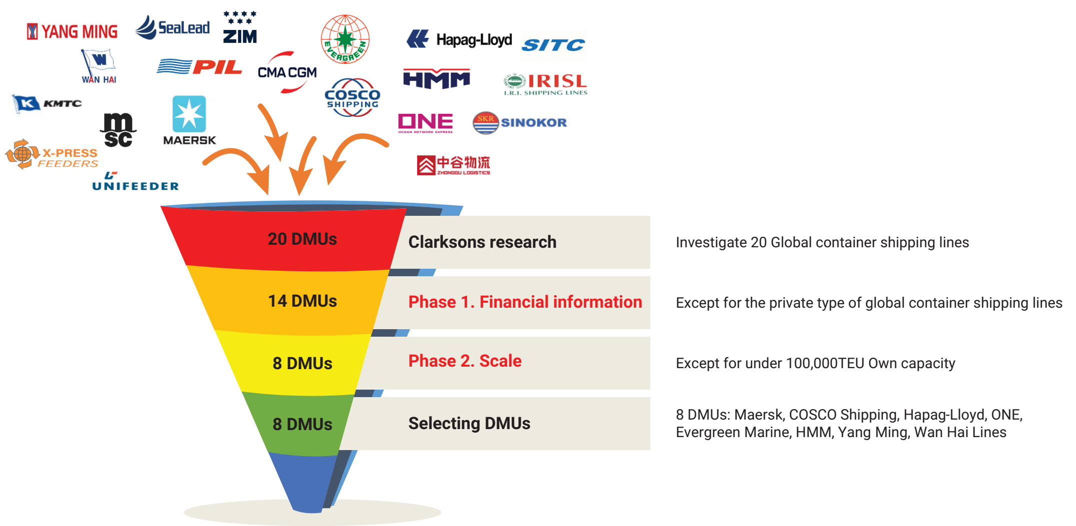

FIGURE 4
Multi-filtering process for selecting DMUs. Source: Author's own compilation.

TABLE 5 Environmental efficiency results of global container shipping companies (GCSCs) in the undesirable output model.

GCSC	Charnes, Cooper, and Rhodes	Banker, Charnes, and Cooper	Scale efficiency
Maersk	0.885	1.000	0.885
COSCO Shipping	0.616	0.635	0.970
Hapag-Lloyd	1.000	1.000	1.000
ONE	0.744	0.780	0.954
Evergreen Marine	0.564	0.623	0.905
HMM	0.789	1.000	0.789
Yang Ming	0.630	1.000	0.630
Wan Hai Lines	0.591	0.774	0.764
Average	0.727	0.852	0.862

Source: Authors' own compilation.

levels of green efficiency were achieved by optimally adjusting the free variables (inputs and outputs in the dataset). For example, Evergreen Marine, which displayed the lowest relative green efficiency in the CCR model, had an efficiency of 0.564. This efficiency was closest to the target when Hapag-Lloyd's weighting reached 50% (Table 6). The study revealed that Evergreen's total assets, own capacity, and CO2 emissions exceeded its total assets by USD 3.316 billion, 373,329,151 TEUs, and 2.487 million tons, respectively, contributing to its low efficiency.

Clarkson Research, in a separate study, analyzed container ship orders through 2027 to identify trends in global liner shipping companies' transition to cleaner alternative fuels (Table 7). The findings showed that first movers consistently plan to order containerships powered by cleaner alternative fuels. Hapag-Lloyd, the carrier with the highest environmental efficiency, has announced plans to order eco-friendly containerships with capacities of 70,980 TEUs, 168,040 TEUs, and 70,500 TEUs between 2023 and 2025. Maersk, the DMU with the largest capacity, also plans to build environmentally-friendly container ships with capacities of 2,100 TEU, 121,200 TEU, 162,600 TEU, 45,000 TEU, and 9,000 TEU from 2023 to 2027. Additionally, HMM, a second-mover, plans to deploy green container ships with capacities of 160,752 TEUs, 54,000 TEUs, and 27,000 TEUs in 2024, 2025, and 2026, respectively. In contrast, most last movers still plan to order containerships that use traditional Bunker C fuel. Therefore, it is expected that a significant environmental efficiency gap will be bridged among global liner shipping companies at each tier level.

4.3 Environmental targets based on the international maritime organization's commitment

This study examines the objectives and strategies of shipping companies transitioning to eco-friendly marine fuel oil, drawing on the sustainability reports of global liner shipping companies. Figure 6 illustrates the findings.

The 2023 IMO strategy for reducing GHGs from ships imposes stricter regulatory standards and incentives than its predecessor. The IMO has set GHG reduction targets, including a 20% reduction by 2030 and a 70% reduction by 2040, relative to 2008 levels, with the ultimate goal of achieving net-zero emissions by around 2050. The strategy includes a plan to convert at least 5% of the total energy used in international shipping to zero or near-zero technologies and eco-friendly marine fuels by 2030. An analysis of ship orders for cleaner marine fuel oil, shown in Table 7, reveals that all but one of the seven shipping lines have set specific GHG reduction targets for 2030, aiming for net-zero by 2050, consistent with the 2023 IMO

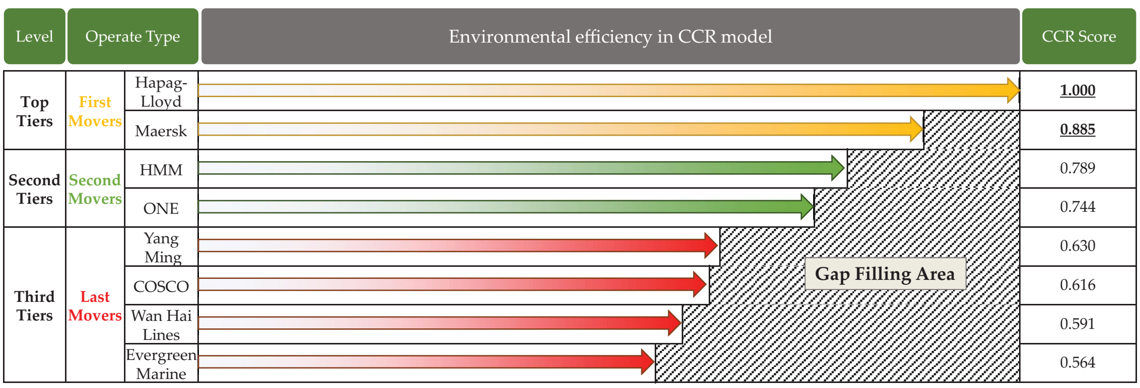

FIGURE 5
Gap filling area by dividing GCSCs into 3 groups based on the environmental efficiency results. Source: Author's own compilation.

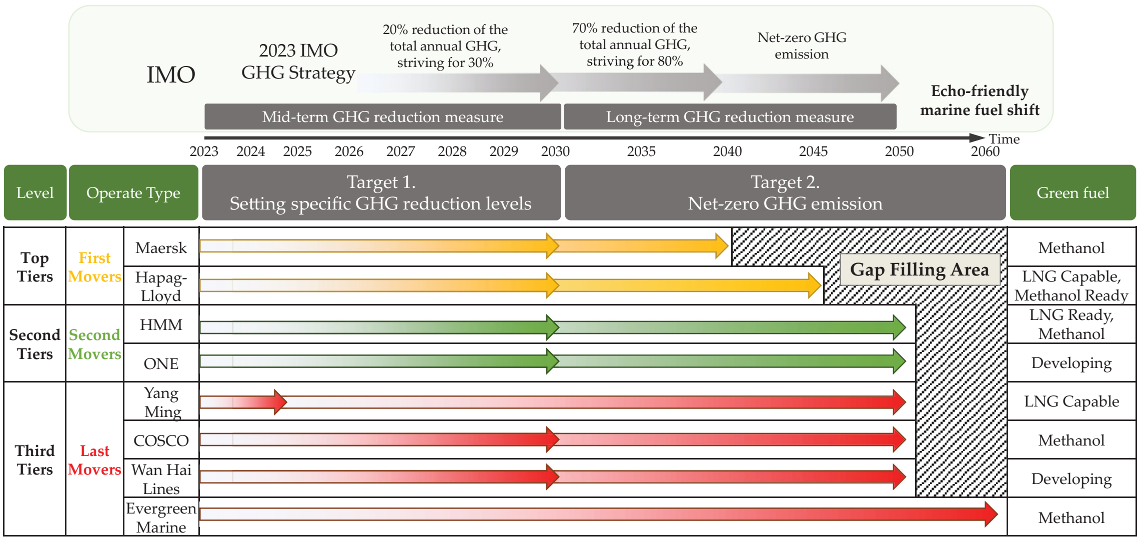

FIGURE 6
Environmental strategies of shipping companies compared to the IMO schemes. Source: Author's own compilation.

TABLE 6 Slack information based on the closest target in the Charnes, Cooper, and Rhodes models.

Variables (unit)	Total assets (billion USD)	Own Capacity (TEU)	Revenue (billion USD)	CO_2 emission (million Ton)
Maersk	1.398	111,113.612	0.000	2.864
COSCO Shipping	5.113	848,974.496	0.000	4.320
Hapag-Lloyd	0.000	0.000	0.000	0.000
ONE	9.820	70,284.215	0.000	0.623
Evergreen Marine	3.316	373,329.151	0.000	2.487
HMM	2.808	133,568.508	0.000	0.019
Yang Ming	0.909	71,631.232	0.000	0.922
Wan Hai Lines	1.615	102,932.770	0.000	1.963

Source: Authors' own compilation.

Strategy. Maersk, the first mover in the top-tier group, aims for net-zero by 2040[1], while Hapag-Lloyd targets 2045[2]. This suggests a leading strategy of transitioning to green shipping fuel. In contrast, COSCO Shipping, the newest member of the third-tier group, has a more gradual target of achieving net-zero before 2060.

The IMO has proposed several GHG reduction strategies for achieving net-zero by 2050, including enhancing energy efficiency design standards and introducing green alternative marine fuels. A detailed review of the eight global liner shipping companies' plans for transitioning to green ship fuels, based on these two strategies, shows that all have plans to improve their vessels' design standards and related equipment for better energy efficiency. These plans include installing energy-efficient propellers, incorporating energy-saving devices, implementing shaft generators, and integrating exhaust/waste heat recycling systems according to the sustainability reports of global liner shipping companies. Specifically, Maersk has set strategies to include new and improved propellers, bulbous bows, shore power enablement and tech solutions like the Maersk's energy efficiency platform StarConnect. Hapag-Lloyd has planned to accommodate duel-fuel propulsion which emit much less CO2. HMM has introduced an energy saving device and ONE has proposed improvement of fuel efficiency and Vessel digitalization program. Yang Ming has adjusted carbon capture devices, bubble drag reduction, energy-efficient wind shields, energy-efficient propellers, shaft generators, and exhaust/waste heat recycling systems. COSCO has announced to implement energy-saving and emission-reduction measures to reduce the use of fuel oil through process control of navigation and shore power transformation.

1 Maersk's sustainability report 2023 (https://www.maersk.com/sustainability/our-esg-priorities/climate-change)

2 Hapag-Lloyd's sustainability report 2023 (https://www.hapag-lloyd.com/en/company/press/releases/2024/03/focus-on-sustainable-shipping–hapag-lloyd-publishes-sustainabil.html)

TABLE 7 Orderbook of global container shipping companies (2023–2027).

Variables	Type	2023	2024	2025	2026	2027
Maersk	General fuels (TEU)	–	–	–	–	–
	Alternative fuels (TEU)	2,100	121,200	162,600	45,000	9,000
COSCO Shipping	General fuels (TEU)	159,220	231,588	144,000	–	–
	Alternative fuels (TEU)	700	700	64,720	24,000	144,000
Hapag-Lloyd	General fuels (TEU)	–	–	–	–	–
	Alternative fuels (TEU)	70,980	168,040	70,500	–	–
ONE	General fuels (TEU)	–	–	–	–	–
	Alternative fuels (TEU)	–	–	–	–	–
Evergreen Marine	General fuels (TEU)	32,648	232,268	148,032	4,600	–
	Alternative fuels (TEU)	–	–	–	192,000	192,000
HMM	General fuels (TEU)	–	5,400	–	–	–
	Alternative fuels (TEU)	–	160,752	54,000	27,000	–
Yang Ming	General fuels (TEU)	–	–	–	–	–
	Alternative fuels (TEU)	–	–	–	77,500	–
Wan Hai Lines	General fuels (TEU)	161,254	70,566	64,620	–	–
	Alternative fuels (TEU)	–	–	–	–	–

Source: Authors' own compilation

Evergreen Marine has replaced old ships with new ones, where optimal energy efficiency and environmental protection are adopted as the concepts of ship design. Furthermore, Evergreen Marine has monitored the fuel consumption of ships and the operating conditions of their main engine to ensure the thrust efficiency of their main engine.

The strategic focus on "green alternative marine fuels" has become crucial in the transition to green marine fuels, particularly in enhancing the competitiveness of global liner shipping companies. Maersk, a pioneer in the top-tier group, led the way by ordering the world's first methanol-powered ship in 2021, spurring the development of green methanol and green ammonia as potential future fuels. In 2023, COSCO Shipping and Evergreen Marine, the last movers in the third-tier group, followed suit by ordering methanol-powered vessels. They are also collaborating with engine manufacturers, shipyards, and marine equipment research institutes on research and development of green methanol, green ammonia, and potential future fuels. Conversely, ONE and HMM, the second movers in the second-tier group, have taken a more cautious approach to the development of green alternative marine fuels, adopting a conservative stance.

4.4 How to achieve net-zero 2050 via the perspective of backcasting theory

To achieve net-zero GHG emissions by 2050, GCSCs must align their strategic plans with the IMO's 2023 strategy for ship emission reduction. This strategy begins with a thorough analysis of the current situation. Companies like Maersk and Hapag-Lloyd are classified as first movers given their superior environmental efficiency. HMM and ONE, with moderate efficiency, are considered second movers, while COSCO Shipping, Evergreen Marine, Yang Ming, and Wan Hai Lines, with low efficiency, are categorized as last movers. Identifying these gaps is crucial for strategic planning. The main gaps include technological challenges given underdeveloped scalable clean fuel technologies, regulatory gaps from the absence of supportive transition policies, and economic gaps from the high costs and financial risks of early green technology adoption.

Figure 7 shows the environmental strategic objectives and carbon neutrality pathways for shipping companies. Strategic targets are set over different time horizons to ensure a structured transition. The initial period (2023-2030) focuses on the development and testing of alternative fuels, implementation of fuel efficiency measures, securing initial funding for pilot projects, and engaging in policy discussions to shape a supportive regulatory environment. The medium-term goals (2031–2040) aim to increase the use of alternative fuels across fleets, expand funding mechanisms, influence global shipping regulations, and promote a wider adoption of energy-saving practices.

The long-term goals (2041-2050) aim for a full transition to sustainable fuels, regulatory support for net-zero goals, sustained investment in green technologies, maintenance of zero-emission operational excellence, and strategy adaptation for all movers to meet environmental standards. The monitoring and evaluation process includes developing and tracking Key Performance Indicators related to fuel use, emissions reductions, and efficiency improvements. Regular assessments will adjust strategies based on technological and regulatory changes, ensuring alignment with global sustainability goals. This comprehensive approach provides

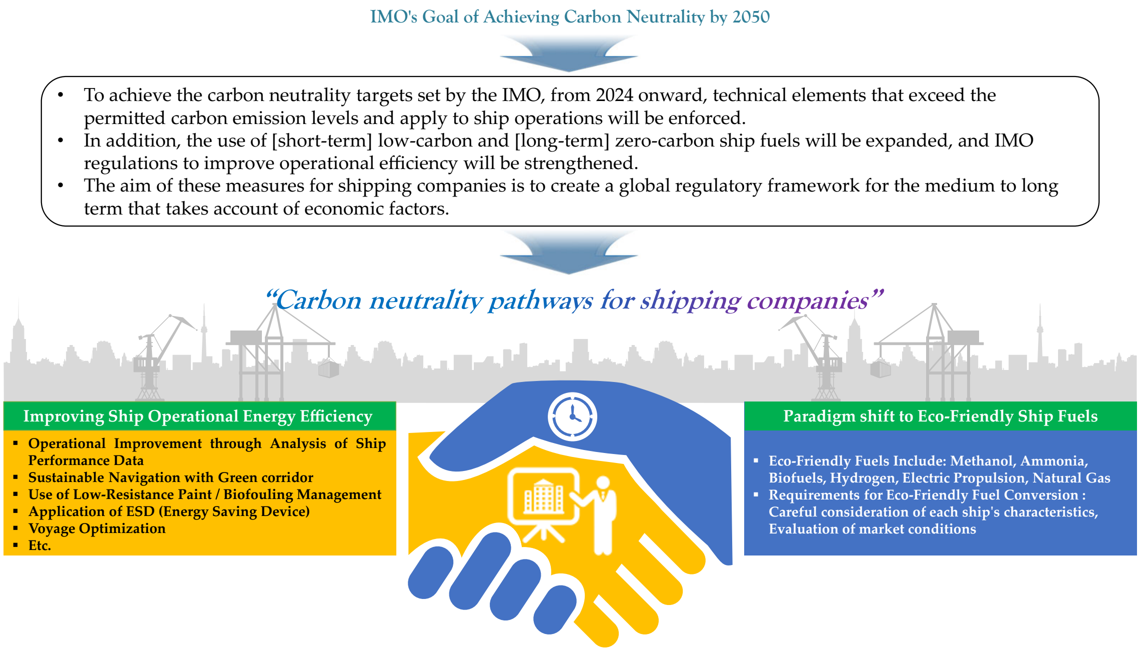

FIGURE 7
Environmental strategic objectives and carbon neutrality pathways for shipping companies. Source: Author's own compilation.

a clear pathway for the shipping industry toward the 2050 net-zero goal, ensuring that the strategic steps are actionable and aligned with global environmental goals.

5 Discussion

Previous research predominantly examines the financial and operational dimensions of shipping efficiency, often overlooking the integration of environmental strategies. Our study employs an extensive dataset to evaluate the effects of adopting green fuels. It provides empirical evidence supporting the strategic benefits of such initiatives, which extend beyond compliance with international regulations to the enhancement of corporate sustainability profiles. This research fills a significant void in the literature concerning the environmental efficiency of GCSCs transitioning to cleaner fuels. With the maritime industry's pressing need to align with the IMO's 2050 net-zero goals, this study is of paramount importance. It illuminates not only the technological and strategic routes that leading GCSCs are adopting, but also underscores the broader implications of such transitions for global supply chains and environmental sustainability. Additionally, this study is important because proposes a formula for calculating CO_2 emissions based on the 2006 guidelines of the Intergovernmental Panel on Climate Change (IPCC) to get around the problem that CO_2 emissions are computed differently by international liner shipping companies owing to different constraints and considerations.

Our analysis-derived environmental efficiency scores underscore the imperative for all GCSCs to continually innovate in fuel technology and fleet management to meet and surpass the stringent IMO emissions targets. Moreover, through the environmental efficiency analysis of GCSCs, we found that Hapag-Lloyd and Maersk are first movers, HMM and ONE are second movers, and Yang Ming, COSC, Wan Hai Lines, and Evergreen Marine are last movers. Moreover, the Gap filling area was examined based on the environmental efficiency score for each of the three groups and the environmental policies according to IMO regulations. Moreover, our findings suggest that the application of backcasting environmental strategies, as proposed in this study, can provide a structured framework for GCSCs to effectively strategize and execute their transitions to sustainable fuels. As a strategy to realize IMO Net-Zero 2050, 6 objectives were set up: Technological Innovation, Regulatory Advocacy, Economic Incidents, Operational Adjustments, Stakeholder Engagement, Scale, and Adaptation. Moreover, for 6 purposes, a detailed strategy was established by dividing it into short-term (2023-2030), medium-term (2031-2040), and long-term (2041-2050) timelines, as depicted in Table 8. In order to achieve technological innovation, developing and testing alternative fuels should be done in the early stages, scale alternative fuel usage across fleets in the mid-term, and achieve full transition to sustainable fuels in the long term. To accomplish regulatory advocacy, policy discussions must be held early on, global shipping regulations must be influenced in the mid-term, and regulations must support Net-Zero goals in the long term. So as to generate economic incentives, pilot projects should receive early funding, middle-stage funding mechanisms should be expanded, and long-term investments in green technologies should be maintained. Implementing fuel efficiency measures early, broadcasting energy-saving practices in the middle, and maintaining operational excellence with zero missions over the long term are all necessary to achieve operational adjustments. Building relationships with important

TABLE 8 Environmental strategic objectives and timelines.

Goal	Objective	Short-term (2023–2030)	Medium-term (2031–2040)	Long-term (2041–2050)
IMO Net-Zero By 2050	Technological Innovation	Develop and test alternative fuels.	Scale alternative fuel usage across fleets.	Achieve full transition to sustainable fuels.
	Regulatory Advocacy	Engage in policy discussions.	Influence global shipping regulations.	Ensure regulations support Net-Zero goals.
	Economic Incentives	Secure initial funding for pilot projects.	Expand funding mechanisms.	Sustain investments in green technologies.
	Operational Adjustments	Implement fuel efficiency measures.	Broad adoption of energy-saving practices.	Maintain operational excellence with zero emissions.
	Stakeholder Engagement	Build partnerships with key stakeholders.	Strengthen collaborations.	Lead global efforts in sustainability.
	Scale and Adaptation	Pilot projects in lead companies.	Widespread adoption by second movers.	Adapt strategies for last movers.

Source: Authors' own compilation.

stakeholders in the early stages, collaborating strongly in the middle, and leading global benefits in the long run are all essential to achieving stakeholder engagement. With a view to achieving scale and adaptation, lead companies must carry out pilot projects in the early stages, be applied throughout the industry by second movers in the mid-term, and last movers should develop strategies in the long run.

To reinforce GCSC's practical strategy in the transition to green fuels, it is critical to integrate advanced digital technologies with alternative fuels to optimize operational efficiency and environmental performance, considering environmental strategic objectives and timelines.

6 Conclusion

This study thoroughly analyzes the environmental performance of GCSCs during their transition to eco-friendly fuel alternatives. It underscores a substantial disparity in environmental performance between early and late adopters. Pioneers, spearheaded by firms like Maersk and Hapag-Lloyd, are at the forefront of embracing sustainable practices. They utilize alternative fuels and cutting-edge technologies to achieve the IMO's net-zero targets for 2050. Conversely, late adopters exhibit a slower transition, indicative of their cautious integration and adaptation strategies, which may potentially delay compliance with global emission standards.

The study's robustness stems from its extensive application of DEA to evaluate not only present efficiencies, but also the potential impact of a complete shift to green fuels. However, the study's reliance on self-reported data from GCSCs introduces limitations, as it may not fully capture operational intricacies or the comprehensive environmental impact of their activities. Future research should strive to include more detailed, real-time data to further substantiate these findings. The high performance of early adopters aligns with anticipated outcomes given their access to advanced technologies and capital. However, the moderate to low efficiency of some firms was unanticipated, necessitating a reassessment of factors that impede or delay the adoption of green technologies, such as financial constraints or technological immaturity. This observation provides a nuanced viewpoint that challenges overly optimistic forecasts of green transitions in shipping.

The study's dependence on secondary data, including company reports and industry databases, restricts the depth of real-time operational insights. It may not fully encapsulate the nuanced challenges associated with adopting green technologies in maritime operations. Furthermore, inconsistent reporting standards across regions and companies can skew comparative analyses and compromise the accuracy of efficiency evaluations.

To enhance the practical strategies of GCSCs in their transition to green fuels, it is crucial to amalgamate advanced digital technologies with alternative fuels to optimize operational efficiency and environmental performance. Establishing collaborative networks with technology providers, policymakers, and industry partners can promote the sharing of best practices and improve access to innovative technologies and financing. Moreover, proactive engagement with regulators can enable GCSCs to influence and anticipate changes in environmental policy, manage compliance costs effectively, and avail incentives for early adopters of green technologies.

Future research should consider longitudinal studies to monitor the long-term efficacy and sustainability of green transitions, devise predictive models to evaluate the impact of various strategic options under different economic and regulatory scenarios, and compare transition strategies across different transport sectors to identify unique strategies and potential synergies. Such research endeavors can yield deeper insights into firms' adaptability and policy effectiveness, particularly considering impending environmental regulations. By addressing these areas, future research can bolster the robustness and applicability of the findings, contribute to the academic discourse on sustainable shipping practices, and aid the formulation of industry and regulatory strategies aimed at achieving global environmental objectives. This comprehensive approach will ensure the shipping industry's pivotal role in global efforts to mitigate climate change. Additionally, if a way to calculate bad outputs like NOx and SOx is developed, it will be able to evaluate the environmental efficiency of GCSCs more elaborately.

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/s.

Author contributions

M-SS: Visualization, Writing – original draft, Writing – review & editing. J-ML: Writing – original draft, Writing – review & editing, Visualization. Y-SK: Supervision, Writing – original draft. D-HJ: Funding acquisition, Resources, Writing – review & editing. C-HL: Writing – original draft, Writing – review & editing.

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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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