The Economics of Decarbonization Regulation: The Case of Shipping Efficiency

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Measures towards net-zero transition need to ensure the well-functioning of the market. This paper focuses on shipping where the existing environmental regulations lack considerations for the industry's economic performance. We apply a stochastic frontier analysis to estimate the carbon, production, cost, and allocative efficiencies for 14 major shipping segments and 664 individual vessels. Our findings suggest that carbon and production efficiencies have increased but cost efficiency has decreased from 2021 to 2024. There is scope for the average vessel to reduce its carbon emissions by 31%. Additionally, fuel is underused by 37% and capital is overused by 58%. Technical inefficiencies increase the total cost by 6%, with market price dynamics increasing it by 17%. The results suggest that, without further policy intervention and clear economic incentivization, there is limited potential for the industry to follow the energy transition pathway.

Introduction

The maritime industry facilitates more than 85% of international trade in goods (Clarksons' SIN, 2024) but, at the same time, is responsible for nearly 3% of GHG emissions (UNCTAD, 2023). In response, the International Maritime Organization (IMO) – the United Nations' specialized body responsible for preventing the marine and atmospheric pollution caused by ships – has set a target of achieving net-zero shipping by or around 2050 (IMO, 2023).

Efficiency maximization is at the forefront of the net-zero transition with various strategies and measures implemented to achieve that. To encourage the adoption of such practices and improve the technical efficiency of vessels, the IMO has introduced a series of measures in recent years, including the Energy Efficiency Design Index (EEDI), the Energy Efficiency Existing Ship Index (EEXI), and the Carbon Intensity Indicator (CII). These can have significant economic implications.

Nevertheless, those measures do not account for the economic-environmental trade-off faced by market participants and, thus, fail to mobilize green investment. Such intervention is crucial as the income generated by greener vessels does not seem to justify the required capital expenditure (Petropoulos, 2022). Therefore, for shipowners to undertake the riskier and more expensive greener investment, there needs to be strong economic (dis)incentives which are not provided by the existing measures.

In response to that, regulators are proposing economic, market-based measures that integrate financial (dis)incentives into energy efficiency requirements or carbon intensity restrictions, such as a maritime GHG emissions pricing mechanism (IMO, 2024), and the European Union's Emissions Trading System (EU ETS), implemented in 2024. Such measures, however, seem to overlook the interrelation between carbon dioxide emissions (CO2) and economic variables as the income generated by a vessel, the capital costs

required for its acquisition or retrofitting, and the labour, maintenance, and fuel costs associated with operating it.

Relevance of the Research Question

This paper relates key economic indicators with technological and environmental measures and assesses the carbon, technical, and allocative efficiencies of the shipping fleet. Furthermore, it introduces a measure that directly relates the economic and carbon performance of a vessel. Based on that, it analyzes the performance of each major shipping segment over the period 2021-2024. Such economic assessments are important for the well-functioning of the industry. Informed by those, policymakers can evaluate the economic implications that environmental measures have on investors and establish a fair system that incentivizes them towards net-zero shipping. The shipping industry, in turn, can identify ways to improve its economic efficiency while complying with the decarbonization regulations.

There are several research gaps this paper aims to fill. First, it proposes an economic measurement of shipping carbon efficiency. Second, it develops carbon, technical, and allocative efficiency measures and assesses the performance of the shipping fleet in recent years. Third, it distinguishes the impacts of economic resource allocation from the effects of technical improvements on the energy demand and total cost of a vessel. Fourth, it compares the price and productivity of energy with other economic inputs at both sector and vessel levels. Finally, it estimates how the above measures vary according to changes in economic inputs and discusses their potential market implications. To the best of our knowledge, this is the first research that thoroughly discusses the economic-environmental trade-off in relation to international trade and transportation.

Data and Methodology

Data are obtained from Clarksons' Shipping Intelligence Network (Clarksons' SIN, 2024) and World Fleet Register (Clarksons' WFR, 2024). These are at vessel type level and individual vessel level for two separate analyses. The first analysis employs panel data for 15 vessel types from 2021 to 2024 at an annual frequency. The second analysis utilizes cross-sectional data from 664 individual vessels in 2023, which is the most recent full calendar year for which actual data were available when performing the analysis.

We use stochastic frontier analysis to measure relative efficiencies (Battese and Coelli, 1992; Kumbhakar and Lovell, 2003). We measure four types of efficiencies, including carbon, production, cost, and allocative efficiencies. *Carbon efficiency*, Optimisation (1), refers to a firm's objective to minimize CO2 subject to output and other inputs. *Production efficiency*, Optimisation (2), corresponds to maximizing output given energy and other inputs. *Cost efficiency*, Optimisation (3), is related to minimizing the total cost given a fixed level of output and inputs. *Allocative efficiency* is defined on the next page.

Carbon efficiency: $min\ (CO2|given\ output\ and\ other\ inputs)$ (1)

Production efficiency: $max\ (output|given\ energy\ and\ other\ inputs)$ (2)

Cost efficiency: $min\ (total\ cost|given\ output\ and\ inputs)$ (3)

Output is measured by either production quantity, such as the vessel's transport work (expressed in ton-miles), or the economic income generated (*e.g.*, vessel earnings). Inputs in the production function include operation, capital, and energy. Operation comprises the crew onboard the vessel, and staff and materials required for repair, maintenance, and technological upgrades. Capital is measured as the newbuilding or resale price of the vessel minus depreciation. As energy consumption is associated with CO2, the latter can be used as a proxy for the former.

Allocative efficiency compares the marginal rate of technical substitution (MRTS) of a pair of inputs with their relative prices (Kumbhakar *et al*., 2015). For example, if the MRTS of energy input over capital input is larger than their relative prices, then energy input is underused and capital input is overused.

Consider minimizing the total cost subject to the production function:

$$min\ \ C = (Lp * OP + Fp * E + Kp * K)$$

subject to (4)

$$ln(D * V)_{it} = \beta_0 + \beta_1 lnOP_i + \beta_2 lnE_i + \beta_3 lnK_i - u_i + v_i$$

where C is total cost, Lp is cost of operation (approximated by wages), *OP* is operation, Fp is the unit cost of energy (fuel price), *E* is energy, Kp is cost of capital (loan rate), *K* is capital, total world seaborne trade ($D * V$) is aggregated by cargo type and measured in ton-miles, u_i is the inefficiency term, and v_i is stochastic noise.

The constraint minimization yields:

$$f_E/f_L = Lp/Fp * exp\ (\varepsilon_1) \quad (5)$$

$$f_K/f_L = Lp/Kp * exp\ (\varepsilon_2) \quad (6)$$

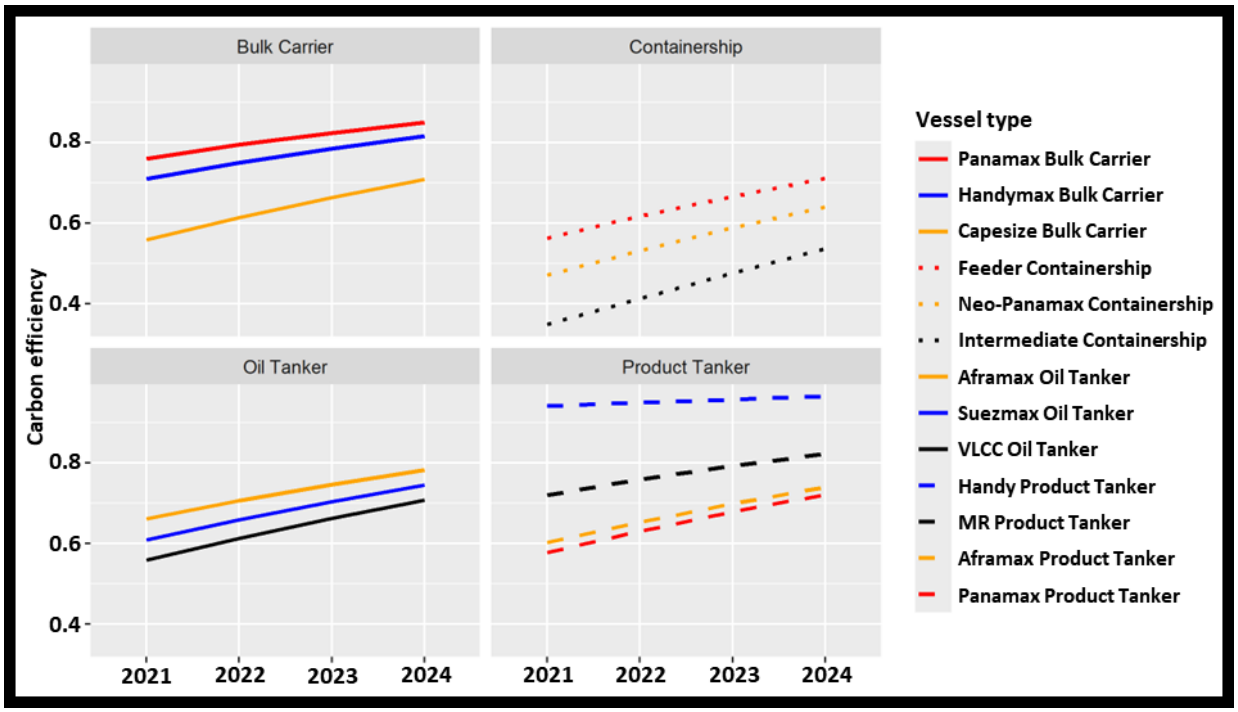
$$f_K/f_E = Fp/Kp * exp\ (\varepsilon_3) \quad (7)$$

where f_K, f_E and f_L are the first-order partial derivatives with respect to capital, energy, and operation respectively; ε_1, ε_2 and ε_3 are the allocative inefficiencies for the input pairs (operation, energy), (operation, capital) and (energy, capital) respectively.

Main Empirical Results

Figure 1 disaggregates the carbon efficiency results by vessel type and year. The minimum carbon efficiency score is 0 and the highest is 1.

Figure 1
Carbon Efficiency by Vessel Type and Year



Abbreviations: "VLCC Oil Tanker" stands for *Very Large Crude Carrier* Oil Tanker; and "MR Product Tanker" stands for *Medium Range* Tanker.

Evidently, carbon efficiency strictly increases in all cases. This suggests improved technical efficiency of vessels, possibly due to recent regulatory measures. The rest of the results are overall in line with the findings and economic justifications. First, containerships are less carbon efficient than bulk carriers and tankers. Therefore, there is more scope for improvement and policy intervention in that sector. Second, the larger the vessel within a sector, the lower the carbon efficiency it generally has. In other words, larger vessels produce more CO2 for a given level of Time Charter (TC) earnings. Future environmental regulations should consider the differences in carbon efficiency across vessel types. A simplified linear model of carbon pricing may cause an undersupply of specific vessel types, negatively impacting the trade of certain commodities.

Figure 2 demonstrates that production efficiency has been strictly increasing in the period 2021-2024 across all vessel types. This trend is in line with the increasing trend of carbon efficiency and reinforces the argument that progress is being made in the technical efficiency of vessels; although, stricter regulatory measures might be needed in the coming years.

Figure 2
Production Efficiency by Vessel Type and Year

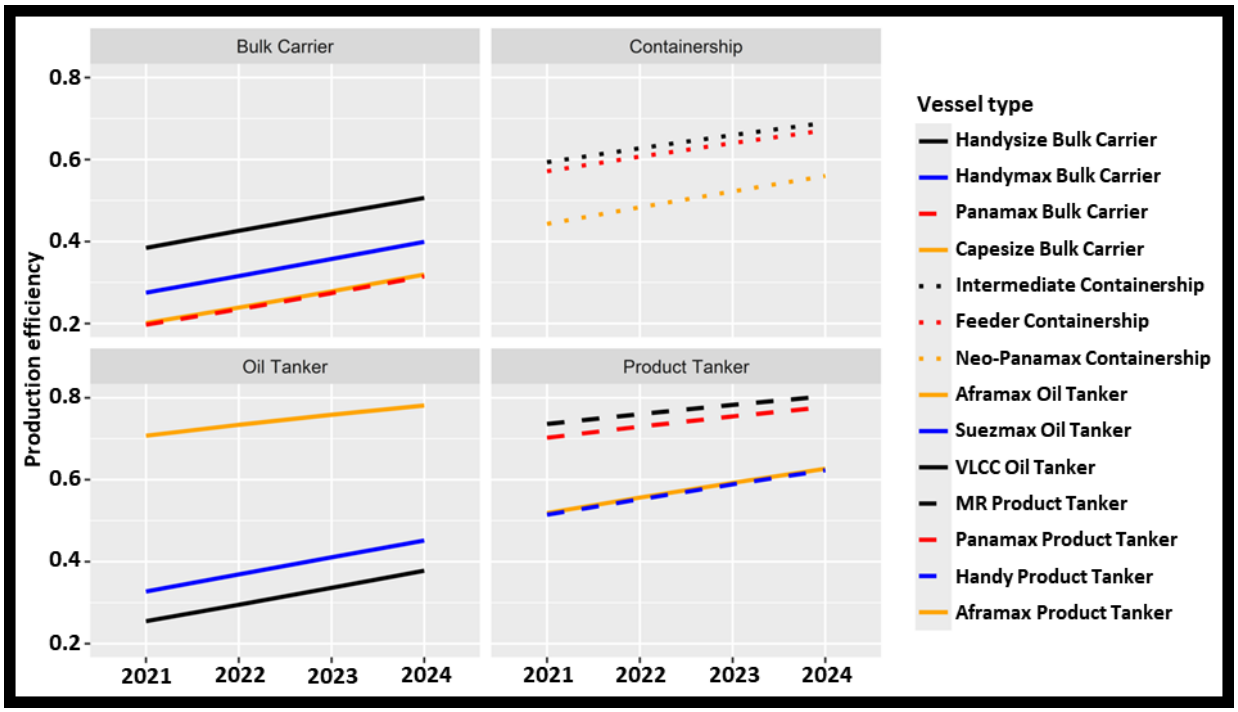


Figure 3 on the next page shows that cost efficiency is declining. This may be explained by the rising costs in shipping due to stricter environmental regulations. Indicatively, eco vessels cost roughly 25% more than their conventional counterparts (Moutzouris *et al.*, 2024). Of particular interest is the fact that cost efficiency has deteriorated more rapidly from 2023 to 2024. One reason for this is the inclusion of shipping in the EU ETS since 2023 which has increased the voyage costs of a vessel. The most important factor though is the Red Sea Crisis and the fact that, as analyzed above, vessels need to sail a significantly larger distance and, thus, burn more fuel when diverting around the Cape of Good Hope instead of transiting through the Suez Canal.

Table 1 below estimates the average effects of technical, allocative, and both inefficiencies combined on the demand for operational inputs, energy, and capital. The technical efficiency focuses on the production and operational capacity of the vessel, *i.e.*, how to maximize transport work with respect to the units of input but without considering their prices. In the "Technical inefficiency" column, a positive value indicates that the average vessel requires a higher amount of input to reach the same level of output compared to the vessel(s) on the efficient frontier. The respective results suggest that the average vessel

overuses operational inputs, energy, and capital by around 6-7%. Such input overuse results in substantial additional costs for the average shipowner/operator.

The allocative efficiency investigates how resources can be allocated more efficiently, *i.e.*, how to minimize the total cost for a given level of transport work based on the prices and productivity of operation, energy, and capital. Combining the technical and allocative efficiencies accounts for both transport work maximization and cost minimization. In the "Allocative inefficiency" column in Table 1 on the next page, a positive (negative) value indicates that the average vessel has overused (underused) the input, *i.e.*, the average vessel should have used less (more) of this input because its price is relatively high (low) compared to the transport work it produces. The magnitude of the allocative inefficiency with respect to operational inputs suggests that this input is overused by more than 2.5 times. With the development of digitization and automation, shipping companies may be able to reduce the operational input required to reach the same level of transport work (subject to safety regulations).

Figure 3
Cost Efficiency by Vessel Type and Year

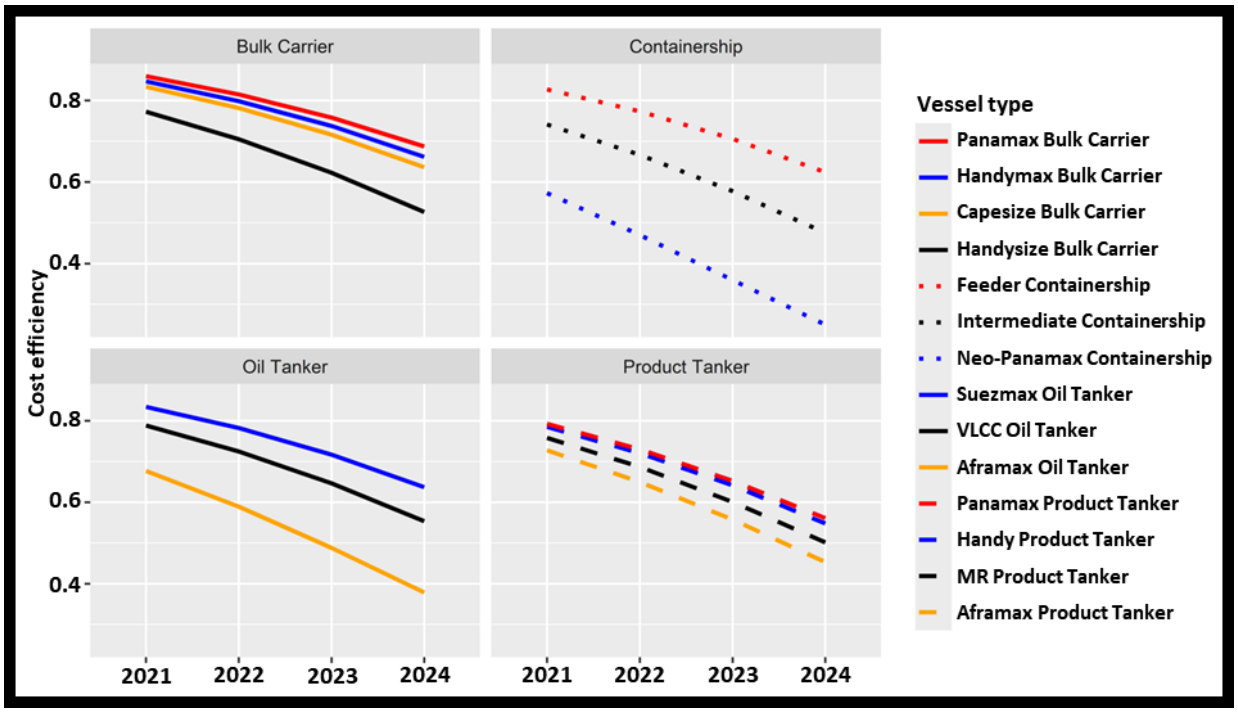


Table 1
The Effects of Inefficiencies on Input Demand of Individual Vessels

	Technical inefficiency	Allocative inefficiency	Both inefficiencies
Operation	7.1%	255.9%	278.0%
Energy	6.1%	-36.5%	-32.6%
Capital	5.9%	57.7%	70.6%

Note: A positive value indicates that, due to inefficiency, the input demand is higher; a negative value indicates the opposite.

The results further suggest that capital is overused by 58%. However, it is rather challenging for shipowners to reduce the capital invested due to regulations that require vessels with higher carbon efficiency. If we consider capital as a quasi-fixed input, an overuse of capital may indicate that the excess capital expenditure needed to comply with the increasingly strict environmental regulations does not generate sufficient return to shipowners.

The energy allocative inefficiency of -37% (Table 1) suggests that fuel input is underused, *i.e.*, fuel is relatively cheap for the transport work it produces. If we consider fuel as a quasi-fixed input due to the exogenous global shipping demand, we may conclude that currently fuel is underpriced. The use of alternative fuels or the introduction of decarbonization regulation would raise the fuel costs. Within a range of 0-37% increase, this would not severely impact the output of vessels, all else equal.

Overall, the effects from allocative inefficiency are much larger in magnitude than those from the technical one, indicating that resource allocation plays a more crucial role in improving the overall vessel efficiency compared to technical adjustments. Specifically, in the meantime, better maintenance of vessels might assist with bringing down the total operating expenses of the vessel.

Conclusion

With the increasing focus on the transition towards net-zero shipping, multiple regulatory measures have been implemented for the industry to comply with. However, those measures do not account for the economic aspect of the transition. Assessing the dynamic relationship between environmental performance, monetary income, and expenditure can be of significant value to shipowners, capital providers, charterers, and regulators alike. This research aims to address this gap by examining the carbon, production, cost, and allocative efficiencies of the shipping fleet.

Our findings suggest that, over the period of 2021-2024, carbon and production efficiencies have increased, but cost efficiency has decreased. Larger vessels are overall more carbon efficient in transporting goods while smaller ones are more carbon efficient in generating revenue. Allocating economic resources appropriately can play the most important role in reducing those costs. We find that fuel is relatively cheap for the transport work it produces. Therefore, while the use of alternative fuels or the introduction of greenhouse gas pricing mechanisms would raise the fuel costs, within a range of 0-37%

increase, this would not severely impact vessels' output, all else equal. Capital is overused by 58%, suggesting that the current return on green investment does not seem sufficient to justify, in purely financial terms, the significant excess investment required.

These findings have strong implications for the industry as they imply that investing in and operating certain vessel types might optimize the economic-sustainability profile of a company. They also yield significant policy recommendations regarding the introduction of economic measures to accelerate the energy transition of the shipping industry. Overall, this research demonstrates the importance of explicitly accounting for the economic dimension when drafting environmental policies for capital and energy intensive sectors with construction lags and volatile cash flows.

Endnotes

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