Scrubber Paper_18Jan2025.docx

by Candidate No : 229677

Submission date: 17-Jan-2025 05:35PM (UTC+0000)
Submission ID: 248862565
File name: Scrubber_Paper_18Jan2025.docx (221.11K)
Word count: 10097
Character count: 56931

Green Investment Under Market Uncertainty: Scrubber Installation in Shipping

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January 2025

Abstract

The International Maritime Organization implemented in 2020 an amendment that limits the sulphur content emitted by vessels. To comply with it, a vessel should either be retrofitted with an Exhaust Gas Cleaning System or burn fuels that emit less sulphur but are more expensive. To examine this dilemma from a business perspective, this paper develops a Vector Error Correction Model that models the causal linkages between the operating income of scrubber and non-scrubber fitted vessels and fuel prices and the green investment decision to retrofit. Our empirical analysis covers the dry bulk and oil tanker sectors which account for three quarters of the industry. The results suggest that the income premium of retrofitted vessels positively depends on the price difference between the fuels and negatively on the relative size of the retrofitted fleet both in the short and in the long run. While the former is in line with market practice, the latter is documented for the first time. Our findings have important implications for ship owners, brokers, charterers, financiers, and policy makers.

Keywords: Sustainable Shipping; Scrubbers; Sulphur Content; Vessel Investment; Net Zero Shipping; Green Investment Efficiency

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Acknowledgments: This work was supported by the UK Department for Transport, as part of the UK Shipping Office for Reducing Emissions (UK SHORE) Programme and the UK Engineering and Physical Sciences Research Council (EPSRC) [grant number EP/Y024605/1].

1. Introduction

Shipping is considered as the backbone of the global economy since it accounts for more than 80 per cent of world trade in terms of volume (Abadie et al., 2017; Clarksons' SIN, 2024). Due to its large scale of operations though, it generates around 2.8% of the global greenhouse gas (GHGs) emissions which are harmful to both human health and the environment (UNCTAD, 2023).

Exhaust emissions mostly include gases like carbon monoxide (CO), carbon dioxide (CO2), nitrogen oxides (NOx), sulphur oxides (SOx), water vapor, and hydrocarbons. Although all elements are destructive, NOx and SOx are of distinctive concern to the environment, vegetation, and the human health. Notably, SOx and NOx emissions arising from shipping activities account for around 15% of the respective total global emissions (Sathi, 2021).

As such, control of gas emissions has become a pressing issue by policymakers and governing bodies to make waterborne trade more environmentally friendly. The International Maritime Organization (IMO) is the governing body assigned by the United Nations, with a mission to protect safety at sea and prevent pollution from ships (IMO, 2019).

Nevertheless, the shipping industry has made unsatisfactory progress in green transition. Currently, . This may be largely attributed to market uncertainty, which discourages potential investors. (evidence of market uncertainty). In this paper, we take the example of scrubber installation as a green investment option to investigate how market uncertainty influences the decision-making process. (mention something about postponed green investment due to market uncertainty in shipping, and we will use scrubber installation as an example to investigate, and figure out a solution to design policy better)

In 2005, Annex VI of the IMO's International Convention for the Prevention of Pollution from Ships (MARPOL) capped the SOx emissions from marine fuels to 4.5% (Tran, 2017). In 2012, it was reduced to 3.5% while, at the 70th Marine Environmental Protection Committee (MEPC) meeting in 2016, IMO decided a further significant reduction of the cap to 0.5% with implementation from 1 January 2020. Alongside this global cap, a stricter 0.1% cap is implemented in sulphur emission control areas (SECA) in the North Sea, the Baltic Sea, and all seas within 200 nautical miles from the coastline of North America.

The exhaust gas cleaning system (EGS), better known as an SOx reducing scrubber device or, simply, scrubber, is a technology installed on vessels to scrub the sulphur content from the high sulphur fuel oil (HSFO) as it is burned by the vessel's main engine. Historically, conventional vessels' main engines burnt

HSFO, with a sulphur content of typically 3.5%. Since 1 January 2020 though, vessels that are not fitted with a scrubber are obliged to burn very low sulphur fuel oil (VLSFO) to comply with the sulphur cap of 0.5%.

This regulation has introduced a dilemma to shipowners regarding whether to equip their fleet with a scrubber or not. Scrubber installation entails a relatively high capital expenditure. Indicatively, for very large crude oil carriers, this can range from $2.5 to $4.5 million (Drewry, 2018). During the installation period, an existing vessel does not earn any operating income for typically one to two months (data by Clarskons' SIN, 2024). Once installed with a scrubber though, the vessel can burn the cheaper HSFO. On the other side, not installing a scrubber allows to resume normal operations without incurring the extra capital expenditure, although, the vessel will be burning the more expensive VLSFO.[1]

Consequently, this investment decision has important financial and commercial implications, as well as complicated impacts on TC premium and fuel spread. As shown in Figure 1, our study aims to explore the complicated relationships between green investment and market prices. Specifically, if the vessel is operated in the spot market, the freight rate received does not depend on whether a scrubber is installed as it is the ship owner and not the charterer who pays for the fuel costs. If the vessel is operated in the time-charter (TC) market though, the freight rate for the scrubber-fitted vessel receives a premium compared to the non-scrubber-fitted one as the charterer reduces their fuel costs by being allowed to burn HSFO instead of VLSFO. As such, one would expect that the TC premium for a scrubber-fitted vessel positively depends on the spread between the VLSFO and HSFO prices. Shipping economic theory suggests that the TC premium should also depend on the availability of scrubber-fitted vessels. However, there are not enough empirical studies examining how fleet supply and fuel spread determine TC premium. What is more, there is a lack of research into how fleet supply, in turn, influences TC premium or fuel spread. Namely, for a given demand for HSFO-burning fleet, increased supply of scrubber-fitted vessels relative to non-scrubber-fitted ones is expected to decrease the premium paid to charter the former instead of the latter.

[1] A third option is to adopt another compliant fuel like liquefied natural gas (LNG) or methanol instead of fuel oil. This solution requires a whole new engine room and mechanism and is proposed solely on new buildings as it does not make any economic sense for an existing vessel to switch and burn alternative fuels. As the decision to incorporate such alternative fuels is mostly associated with the reduction of CO2 emissions and not of Sox, it is out of scope of this paper to model it. Other alternatives (not for propulsion) have been picked up on but are at least for now farfetched; these include solar panels, vertical wind turbines, balloons with helium, kites (Yildirim, 2021).

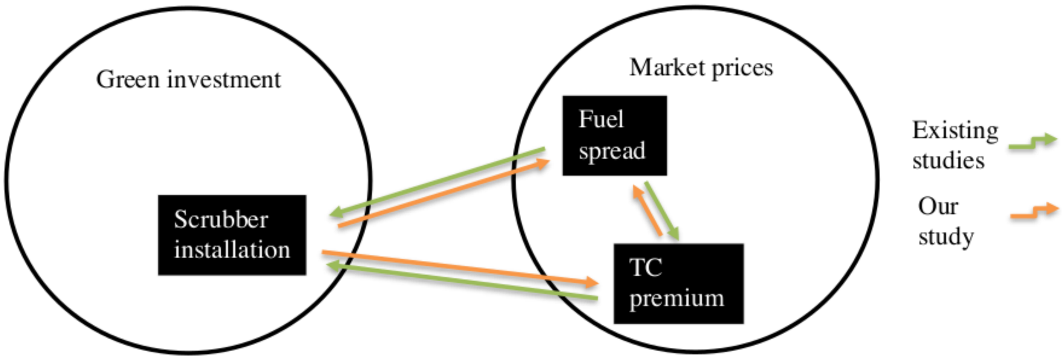


Figure 1 Our contributions to green investment under market uncertainty

Our paper aims to address the literature gap regarding the lack of comprehensive investigation into green investment under market uncertainty in transportation. To the best of our knowledge, no study has fully explored the causality and reverse causality from market prices to green investment decisions with real observations in shipping. More specifically, no study has employed a robust method to disentangle the relationships between TC premium, fuel spread and scrubber installation. Our main research questions are (a) do income and fuel prices drive the investment decision of scrubber installation? (b) Does scrubber investment affect these market prices in return?

Using data from 2020 to 2024 for various shipping segments, this paper examines what drives the TC premium in practice. Answering this question has important industry implications as it can inform shipping and chartering companies' commercial policies as well as shipbrokers' assessments of future TC rates. Furthermore, this paper investigates whether financial incentives, as the TC premium and fuel spread, determine the shipowner's investment decision and, in turn, the size of the scrubber-fitted fleet. We also examine whether the demand for HSFO-fuelled vessels negatively affects the spread between VLSFO and HSFO prices. From a policy perspective, this can build evidence on whether improved financial performance of vessels drives the industry's investment in green shipping technologies. It can also provide clarity about whether the shipping demand for different fuel types affects their prices and availability. This is important from both an energy security and supply-chain resilience perspective.

From a methodological point of view, we expand the current literature by introducing a multivariate time series model which builds on established shipping economic theory and adjusts to account for the case of sustainable investments. We develop a theoretical economic framework which investigates the dynamic casual linkages between vessel income premia, fuel price differentials and the relative share of green investment by means of a Vector Error Correction (VECM) model. The empirical analysis sheds light on the causal transmission patterns among those variables at both short- and long-run horizons and allows us to establish the existence of a common long-run equilibrium among the series. We also test the dynamics of the long-run relationships, namely, the relative impact of the changes of one series on the other series and on the convergence to the equilibrium, if any, as well as by how much this has been influenced by recent shocks.

The rest of the paper is structured as follows. Section 2 provides a literature review and a technical background to the study. Section 3 introduces the data and the empirical framework. Section 4 presents and discusses the results. Section 5 concludes.

2. Literature review

Various academic papers and industry reports have studied exhaust gas cleaning systems as a solution to comply with the IMO regulations, their mechanics, environmental concerns, and their economic efficiency. Whilst a number of studies focus on the technological aspect, not many have fully explored the scrubber installation as an investment decision on financial foundations. Table gives an incomprehensive summary of the papers analysing the investment decision of installing scrubber on financial foundations.

Table 1. Summary of literature related to the financial aspects of scrubber installation.

Literature	Methodology	Variables	Conclusions
Andersson et al., 2020	Lifecycle analysis, sensitivity analysis, cost assessment, calculation of payback period	Fuel price	The open-loop scrubber offers a slightly shorter payback period (0.4-0.5 years) compared to the closed-loop scrubber across various scenarios.
Bekdaş et al., 2023	Calculation of net present value (NPV) and payback period	Vessel type, interest rate, lifetime, fuel price	Opting for VLSFO for dry cargo ships, hybrid scrubbers for crude oil tankers, open-loop scrubbers for container ships, and hybrid scrubbers for Ro-Ro ships is generally found to be economically advantageous in most scenarios.
Jang et al., 2020	Lifecycle analysis (construction, operation,	Vessel type, lifetime	The age and power of a vessel are significant parameters for evaluating a scrubbers emission reduction level and its economic sense.

	maintenance, and scrapping)		
Jiang et al., 2014	Cost benefit analysis, calculation of NPV	Fuel price, lifetime, interest rate	The price difference between MGO and HSFO plays a crucial role in this decision. MGO generally has higher net present values compared to scrubbers when the fuel price spread is below 231 Euros per ton. Additionally, installing a scrubber on new ships is more advantageous than retrofitting existing ones. Older ships with less than 4 years of remaining lifespan are not suitable for scrubber installations.
Karatuğ et al., 2022	Calculation of NPVs and payback period	Vessel type, interest rate	The discounted payback period is calculated to be 0.34 years at a 5% discount rate and 0.37 years at an 8% discount rate. This makes it clear why shipping companies would find scrubber installations justifiable.
Huang and Hua, 2022	Calculation of NPV	Fuel price, interest rate, speed, ECA, freight rate, lifetime	Implementing a speed differentiation strategy can lower the economic costs associated with the VLSFO method, thereby diminishing its cost disadvantage compared to scrubbers. Additionally, a lower discount rate would favour the scrubber option.
Lee, 2022	Lifecycle analysis, NPV calculation	Emission Control Area (ECA), ship lifecycle, lifetime, fuel price, interest rate	The case study of 72,100 gross-ton cargo ships indicates that closed-loop scrubber systems are the most economically and environmentally effective option compared to open-loop or hybrid systems.
Lunde et al., 2024	Calculation of payback period, simulation of global scrubber-vessel activity	Fuel price, operational expenses	Within five years of installation, over 95% of ships equipped with the most common open- and closed-loop scrubber systems achieve break-even. However, the cost of marine ecotoxicity damage indicates that private economic gains come at the expense of marine environmental health..
Panasiuk and Turkina, 2015	Calculations of NPV, payback period, and internal rate of return	ECA, lifetime, interest rate, fuel price (current and previous prices)	With increase in fuel prices, the scrubber solution becomes even more profitable and vice versa. Thus, the difference in fuel prices is the key parameter influencing the profitability of the investment.
Reynolds et al., 2011	Life cycle analysis, calculation of NPV, payback period and internal rate of return, sensitivity analysis	ECA, vessel type, fuel price, interest rate	The cost savings potential coming from the scrubber always remains significant, with positive NPVs in all scenarios positive and the best being the route spent the most time in an ECA zone.
Wu and Lin, 2020	Cost benefit analysis	Fuel price, lifetime	For the first 3.3 years after scrubber installation, the cost-benefit ratio is more favorable compared to the VLSFO strategy. Therefore, the VLSFO strategy, which

			emits fewer pollutants, is a more suitable compliance strategy for periods exceeding 3.3 years.
Yang and Zou, 2023	Cost assessment, sensitivity analysis	ECA, speed, vessel fuel type	Currently, the most economical choice is to continue using HSFO with installed scrubbers. If the proportion of sailing time within the ECA is less than 14%, Marine Gas Oil (MGO) becomes the most expensive option. Conversely, when the ECA ratio exceeds 47%, methanol emerges as the best option for both cost and environmental benefits.
Zhu et al., 2020	Cost benefit analysis, sensitivity analysis, calculation of NPV and annual unit cost	Fuel price, interest rate, lifetime	A scrubber is generally more appealing, except in two scenarios where VLSFO is preferred. Specifically, a scrubber becomes less attractive when VLSFO and MGO prices move in the same direction with a price spread of $56 per ton or less, and when HSFO prices rise while MGO prices fall with a price spread of $16 per ton or less.
Zis et al., 2022	Calculation of NPV and payback period	Vessel type, fuel price, speed, ECA	Scrubber investments yield higher profits during periods of elevated fuel prices and for ships that spend more time at sea. The paper also indicates that the potential for speed differentiation within and outside ECAs has decreased.

Note: The methods and variables in the table only include those related to financial investment. Only variables of which the influence on investment has been modelled/discussed are displayed.

In Table, the studies have employed a variety of methods, but most, if not all, methods are based on assumptions. There is a lack of evidence-based method. The most frequently used methods include: 1) lifecycle analysis; 2) cost benefit analysis; 3) sensitivity analysis; 4) calculation of net present value (NPV) and payback period. Lifecycle analysis typically examines the costs associated with the entire lifecycle of a scrubber system, encompassing construction, operation, maintenance, and disposal (Andersson et al., 2020; Jang et al., 2020; Lee et al., 2022; Reynolds et al., 2011). This method offers a more comprehensive evaluation of the investment decision, as opposed to merely considering capital investment and operational profit. Cost-benefit analysis goes beyond cost consideration by comparing it with the accrued benefits, providing a more robust assessment than mere cost evaluation (Jiang et al., 2014; Wu and Lin, 2020; Zhu et al., 2020). Sensitivity analysis identifies the key variables that influence the investment decision in scrubber installation (Andersson et al., 2020; Reynolds et al., 2011; Yang and Zou, 2023; Zhu et al., 2020). It is an effective tool for navigating market uncertainties, as the decision to install a scrubber versus using VLSFO can fluctuate with changes in interest rates and fuel prices. Sensitivity analysis determines under which conditions one decision may be favoured over another. Lastly, the calculation of NPV and payback periods is a common approach in the literature (e.g., Bekdaş et al., 2023; Karatuğ et al., 2022; Panasiuk and Turkina, 2015; Zis et al., 2022).

This method accounts for the time value of money by considering the discount rate on investments, offering a more substantial basis than simple, non-discounted cost calculations. Given that shipping investments can span up to 20 years, discounting future earnings to their present value is crucial. However, all these methods make assumptions and test whether a scrubber installation is worthwhile based on assumptions. None of the studies has observed the real financial benefits from scrubber investment. This study will *not* follow the above studies but will apply an evidence-based econometric method, VECM, with real observations on the income generated by scrubber installation (TC premium).

In Table, the studies focus on answering the question *whether* scrubber installation is preferred over VLSFO but neglect the fact that the market prices and scrubber investment may interact with each other. An increase in market price may drive up the scrubber investment, and reversely, an oversupply of the investment may reduce relevant market price. The studies conduct static scenario analyses assuming that decision of scrubber installation does not influence market prices. Based on their assumptions, the main conclusion is that scrubber installation is preferred under four conditions: a) when the fuel price spread is high between VLSFO and HSFO; b) when the remaining lifetime of the vessel is long; c) when the interest rate or the discount rate is low; d) when the vessel sails through Emission Control Area (ECA) often. There is no consensus regarding the exact criteria for choosing scrubber installation or using VLSFO. In fact, the criteria for installing scrubber, or not, vary largely depending on the vessel type, route and assumptions made in the studies. For example, in terms of oil spread, Jiang et al. (2014) find that MGO generally has higher net present values compared to scrubbers when the fuel price spread is below 231 Euros (approximately 252 USD) per ton; in comparison, Zhu et al. (2020) find that MGO is more attractive when the fuel price spread is equal to or below 56 USD per ton. In terms of payback period, Karatuğ et al. (2022) find that the discounted payback periods of scrubber investment are 0.34 and 0.37 years under 5% and 8% discount rates; in comparison, Wu and Lin, (2020) find that the scrubber option is preferred when the remaining payback period is over 3.3 years. The large uncertainties in shipping investment call for robust and sophisticated methods that can address the multiple causalities between green investment and market uncertainty.

In Table, the studies consider a range of variables, such as fuel price, vessel type, interest rate, remaining lifetime of the vessel, and whether the vessel goes to emission control areas. As the studies make assumptions that investment decision does not affect market prices, they neglect a core variable ---- the fleet supply of scrubber-fitted vessels. The fleet supply is high if a large number of investors decide to install scrubbers, which may, in turn, reduce the fuel spreads or TC premium of scrubber-fitted vessels. Our study considers the fleet supply variable to address the multiple causalities between investment decision and market prices.

In sum, different from the above studies, our study employs VECM to explore the market uncertainties in scrubber investment based on real observations of additional income. We investigate the multiple causalities among fuel spread, fleet supply, and TC premium of scrubber-fitted vessels. In doing so, we explore the relationships between green investment and market uncertainties, rather than providing a "yes" or "no" decision to green investment based on assumptions. To the best of our knowledge, no study has fully addressed these literature gaps.

Regarding the big picture of shipping decarbonising, our research has contributed to the understandings of green investment and market uncertainty. A large group of scholars focus on the adverse effects of policy uncertainty on green investment, but few have explored green investment in the context of market price fluctuations.

3. Data and Methodology

3.1. Data Description

We collect weekly frequency data from Clarksons' Shipping Intelligence Network platform for the period 08/05/2020 to 23/08/2024 on: 1-year time-charter rates for both scrubber- and non-scrubber-fitted vessels, in terms of $US/day; prices of HSFO and VLSFO, in terms of $US/tonne; and the scrubber-fitted and total fleet development, in terms of deadweight tonnes (DWT, which is the conventional measure of a vessel's cargo-carrying capacity).[2]

We focus on all segments for which there is availability of TC rate data for both scrubber- and non-scrubber-fitted vessels. Those comprise VLCC, Suezmax, Aframax, Panamax, and Handysize in the tanker market and Capesize (Pacific and Atlantic region) in the dry bulk market.[3] The vessels in a given segment only differ in whether they have a scrubber installed or not. This allows us to focus on the effects of scrubber installation. In total, the sample consists of 225 observations for each tanker segment (08/05/2020 to 23/08/2024) and 195 for each dry bulk one (04/12/2020-23/08/2024).

[2] Data on fleet development are available only at a monthly frequency. We apply Chow-Lin method on the monthly time series to transform them into a weekly frequency time series. The robustness of the method to unit roots is discussed in Silva and Cardoso(2001)

[3] Very Large Crude Carriers (VLCC) vessels have a typical transport capacity of 318,000 DWT; Suezmax of 157,000 DWT; Aframax of 115,000; Panamax of 74,000 DWT; and Handysize of 38,000 DWT. Those vessels are associated with the transportation of crude oil. Capesize vessels have a typical transport capacity of 180,000 DWT and are mainly associated with the transportation of iron ore and coal.

To examine the income premium received by scrubber-fitted over non-scrubber fitted vessels, the $spread_{j,t}$ variable is constructed:

$$income_{j,t} = {TC_{j,t}^{SOx}}/{TC_{j,t}} - 1, \qquad \text{(Eq.1)}$$

where $TC_{j,t}^{SOx}$ and $TC_{j,t}$ are the 1-year TC rates for scrubber-fitted and non-scrubber-fitted eco-vessels respectively, and j denotes the respective market segment. This reflects the operating revenue benefit to the shipowner, from installing a scrubber, when the vessel is employed in the time-charter market.

When the scrubber-fitted vessel is employed in the spot market, while there is no direct benefit in the form of higher freight rates, the shipowner's operating profit still increases due to burning HSFO instead of VSLFO. Namely, VLSFO is more expensive than HSFO as it is a more refined product but also because of the lack of supply capacity given the increasing demand for it. This price premium is quantified through the $fuel_t$ variable:

$$fuel_t = {VLSFO_t}/{HSFO_t} - 1, \qquad \text{(Eq.2)}$$

where the price for each of the two different fuel oil grades, i.e. $VLSFO_t$ and $HSFO_t$, is estimated as the average fuel cost incurred in the major bunkering ports of Houston, Rotterdam and Singapore.

As it can be observed in Figure 1, the price differential between VLSFO and HSFO has been highly volatile, ranging from roughly $50 to more than $350 over the period 2020-2024. Furthermore, it follows the performance of brent crude oil prices very closely; for the whole period, the correlation stands at 67% (data by Clarksons' SIN, 2024). However, since 2022 and the rise of geopolitical risks (war in Ukraine and the resulting sanctions; tensions in the Middle East region) which have diverted the oil market from its normal trajectory, the relationship between VLSFO/HSFO spread and oil prices seems to have been broken, although still positive but at low levels (Figure 2, data by Clarksons' SIN, 2024).

Figure 1. VLSFO/HSFO spread ($ terms) and Brent Crude Oil price ($/bbl, 1-month future contract).

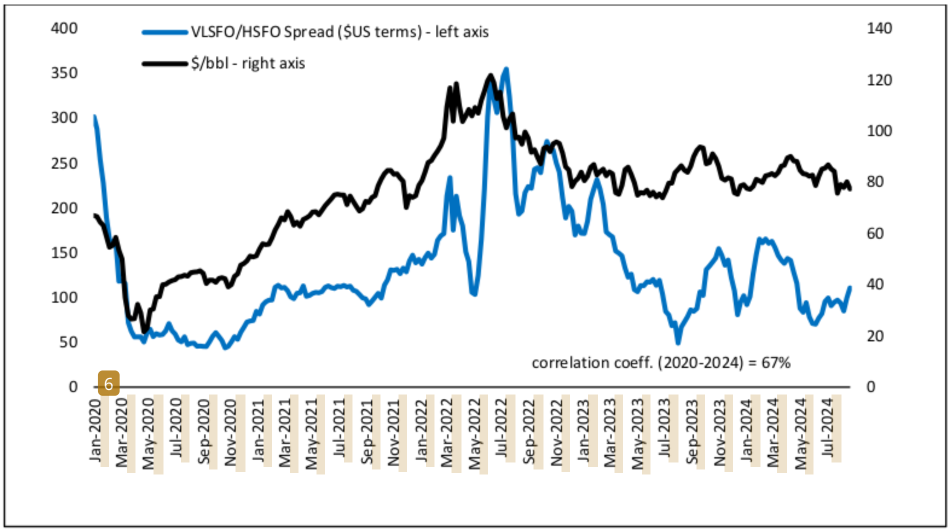
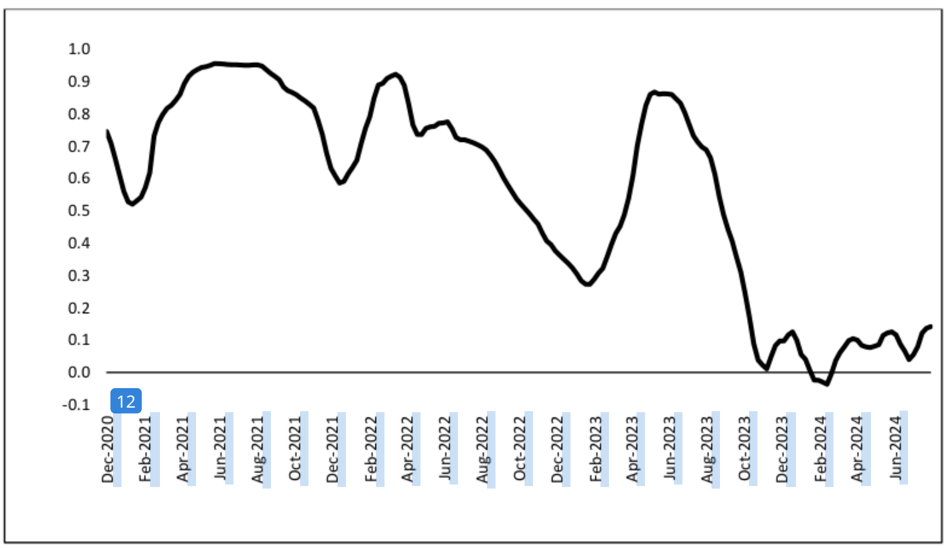


Figure 2. 1-year rolling correlation between VLSFO/HSFO spread and Brent Crude Oil price.



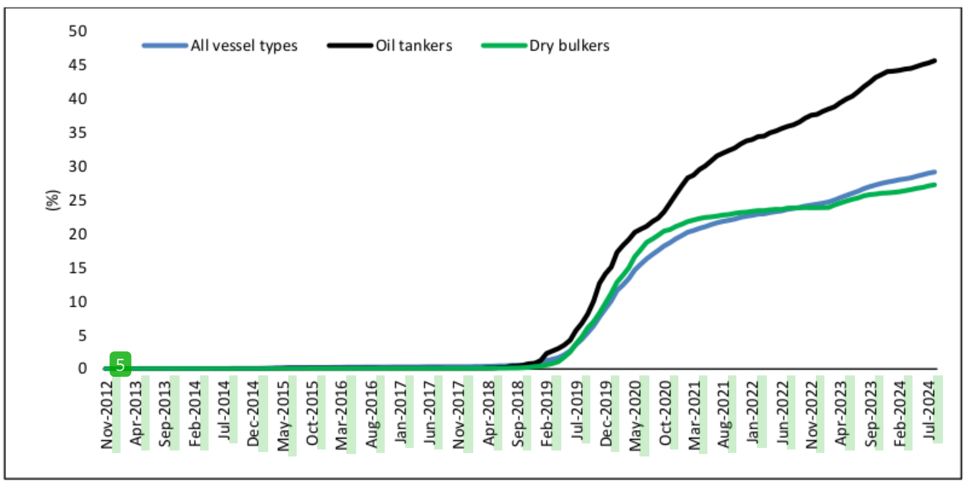
By including the income and fuel variables, therefore, our empirical investigation aims to capture the relative financial performance of scrubber-fitted vessels as well as the demand for such vessels on behalf of charterers. It is important to note that the associated capital expenditure, i.e. the cost of scrubber installation, is not included as a variable in the empirical estimation since it is rather fixed and no relevant time-series data are available.

We also examine whether the composition of the fleet affects the financial performance of scrubber- relative to non-scrubber-fitted vessels but also what determines the scrubber investment decision of ship owners. To that end, the supply of the scrubber-fitted fleet, $supply_{j,t}$, is quantified as the percentage of the overall fleet in that segment, $fleet_{j,t}$, that is scrubber-fitted, $fleet_{j,t}^{SOx}$:

$$supply_{j,t} = {fleet_{j,t}^{SOx}}/{fleet_{j,t}}, \qquad \text{(Eq.3)}$$

As Figure 3 suggests, close to the time of the implementation of the new regulation, scrubber installation sharply increased, i.e. from 1.3% of the total fleet (in DWT terms) in January 2019 to 11.2% within a year. However, while the share of scrubber-fitted fleet is continuously increasing, the pace of adoption has slowed down since 2021. As of August 2024, 29.2% and 5.3% of the total fleet in terms of DWT and number of vessels, respectively, are scrubber-fitted. For the tanker sector, the two figures correspond to 45.7% and 37.6% and for the dry bulk one to 27.3% and 13.9% (data by Clarskons' SIN, 2024). This suggests that, first, less than half of the fleet are scrubber-fitted – and, thus, burn VLSFO – and, second, there is a tendency for larger vessels to be retrofitted as opposed to smaller ones. The latter implies that the scrubber system is less efficient on smaller vessels. Oil tanker vessels, not only have the highest rate of adoption, but the DWT and number figures are much closer to each other, suggesting that also smaller vessel types are fitting that technology. Finally, as of August 2024, 71.2% of dry bulkers and 69.1% of tankers are retrofitted, indicating that most vessels (in DWT terms) install the technology after they have been built.

Figure 3. Share of scrubber-fitted vessels as a percentage of the total respective fleet (in DWT terms).



3.2. Diagnostic Tests and Descriptive Statistics

We first assess whether the variables under consideration – i.e. income, fuel, and supply – are non-stationary or characterised by a unit root, i.e. integrated of order one, $I(1)$. In view of the limitations of classical unit root tests, we conduct several tests, namely the Augmented Dickey Fuller (ADF 1979), the Phillips Perron (PP 1998), and the Kwaitkowski, Phillips, Schmidt and Shin (KPSS 1992) tests, to establish the order of integration. The econometric unit-root literature has focused on the inability of unit-root tests to distinguish in finite samples the unit-root null from nearby stationary alternatives (Christiano and Eichenbaum 1990; Rudebusch 1993). To ensure robustness of our conclusions and measure the persistence of the unit root, we derive the 90% the confidence intervals (CIs) for the largest unit root (Stock 1991) .

The CIs provide an assessment of the persistence of the root, since they present the range of values of the root that are consistent with the data. The CI estimates suggest that the unit root is quite persistent with all lower bounds quite clearly above 0.80 for both the ADF intercept only (ADF(μ)) and ADF trend and intercept (ADF(τ)). Furthermore, the Geweke and Porter-Hudak (1983) test for or fractional integration, quite uniformly suggest that most estimates of *d* fall significantly in the neighbourhood of one. Finally we conduct the Perron (1997) unit root test to allow the evaluation of the null hypothesis of integration under the presence of structural breaks , allowing for breaks in intercept and trend.

To check that these series are not integrated of higher orders, the tests are repeated using first differences of each series. The results, reported in Table 2, for the levels and in Appendix Table XX for the first difference of all series, suggest that levels of all series are non-stationary, while their first differences are stationary, indicating that the variables are integrated of order one, I(1).

Table 2. Unit Root Tests

	PP	*KPSS*	ADF(μ)	ADF(τ)	*GHP*	*CI ADF*(μ)	*CI ADF*(τ)	Perron
$income_{vlcc}$	−0.339 (0.9861)	1.9832	-2.317 (0.1465)	-2.128 (0.5267)	0.937 (0.362)	(0.89, 1.03)	(0.92, 1.04)	-4.460 (0.134)
$supply_{vlcc}$	−0.302 (0.9962)	1.8877	-2.422 (0.1366)	-2.9426 (0.1152)	0.897 (0.286)	(0.87, 1.03)	(0.89, 1.03)	-4.88 (0.128)
$income_{suezmax}$	−0.266 (0.7487)	1.8230	-2.128 (0.2238)	-3.062 (0.1135)	0.834 (0.256)	(0.84, 1.02)	(0.78, 1.03	-4.39 (0.142)

$supply_{suezmax}$	−0.800	1.9601	-2.844	-2.887	0.894	(0.89, 1.03)	(0.98, 1.05)	-4.59
	(0.8378)		(0.1180)	(0.1947)	(0.384)			(0.137)
$income_{aframax}$	−1.894	0.9643	-3.022	-3.088	1.072	(0.92, 1.01)	(0.88, 1.03)	-4.33
	(0.0761)		(0.0923)	(0.1156)	(0.397)			(0.145)
$supply_{aframax}$	−0.295	0.9451	-2.725	-2.437	0.904	(0.98, 1.04)	(0.89, 1.04)	-4.07
	(0.6648)		(0.0851)	(0.344)	(0.288)			(0.875)
$income_{panamax}$	−0.921	1.7501	-3.074	-3.512	0.937	(0.95, 1.04)	(0.94, 1.04)	-4.52
	(0.9837)		(0.1136)	(0.345)	(0.362)			(0.186)
$supply_{panamax}$	−0.340	1.0572	-1.051	-2. 672	0.899	(0.96, 1.03)	(0.98, 1.05)	-4.36
	(0.8432)		(0.7345)	(0.256)	(0.316)			(0.144)
$income_{handysize}$	−0.308	1.9081	-1.134	-2. 851	0.834	(0.99, 1.02)	(0.89, 1.04)	-4.45
	(0.9432)		(0.5642)	(0.234)	(0.256)			(0.138)
$supply_{handysize}$	−0.273	0.8752	-2.452	-2.363	0.905	(0.91, 1.04)	(0.87, 1.03)	-4.57
	(0.9532)		(0.1288)	(0.3978)	(0.287)			(0.167)
$fuel_{tanker}$	−0.385	1.0326	-1.323	-3.062	0.902	(0.91, 1.04)	(0.89, 1.04)	-4.02
	(0.9765)		(0.5632)	(0.1881)	(0.290)			(0.102)
$income^{atlantic}_{capesize}$	−0.222	0.8864	-1.127	-2.387	0.908	(0.99, 1.04)	(0.80, 1.03)	-4.43
	(0.8245)		(0.6573)	(0.1135)	(0.280)			(0.115)
$income^{pacific}_{capesize}$	−0.283	0.9523	-1.265	-2.567	0.834	(0.95, 1.03)	(0.89, 1.03)	-4.58
	(0.8711)		(0.4871)	(0.1167)	(0.256)			(0.135)
$supply_{capesize}$	−0.317	1.0531	-2.346	-3.102	0.905	(0.98, 1.03)	(0.97, 1.05)	-4.24
	(0.9053)		(0.4673)	(0.1682)	(0.256)			(0.128)
$fuel_{drybulk}$	−0.330	1.3765	-2.341	-2.557	0.904	(0.99, 1.04)	(0.95, 1.03)	-4.56
	(0.9218)		(0.2043)	(0.2552)	(0.288)			(0.122)

The table shows all unit root test for the series in levels. PP is the Phillips and Perron (1988) test with intercept and trend, McKinnon one sided p-values are reported in parentheses. KPSS is the Kwiatkowski, Phillips, Schmidt, and Shin (1992) test with intercept and trend, the 1% and 5% critical values are respectively 0.739 and 0.463. ADF(μ) and ADF(τ) are the Augmented Dickey and Fuller (1981) test respectively with intercept and intercept and trend, MacKinnon one sides p-value are reported in brackets. Lag length selection is based on the minimisations of the SBIC in the test equation for all tests. The 90% CIs are constructed using Stock's (1991) technique for the largest autoregressive root. GHP is the Geweke and Porter-Hudak (1983) estimates of the order of integration, standard errors are reported in brackets. The last column reports the Perron(1997) test for unit root under structural break in trend and intercept.

Table 3. Descriptive Statistics

The sample period is 08/05/2024 to 23/08/2024 for the tanker market, and 04/12/2020 to 23/09/2024 for the dry bulk market. $\bar{x}$ denotes the mean, SD the standard deviation, $\hat{\alpha}^3$ and $\hat{\alpha}^4$ the skewness and kurtosis, respectively. JB is the Jarque and Bera (1980) $\chi^2(2)$ distributed test statistic for normality. $Q(10)$ is the Ljung and Box (1978) Q statistic on the 10th-order sample autocorrelations of the raw series, distributed as $\chi^2(10)$.

	$\bar{x}$	SD	$\hat{\alpha}^3$	$\hat{\alpha}^4$	JB	p-value	$Q(10)$	p-value	Obs.
$\Delta income_{vlcc}$	0.0033	0.0741	-0.53	14.93	1,339.28	0.00	523.50	0.00	224
$\Delta supply_{vlcc}$	0.0036	0.0034	1.68	5.56	164.99	0.00	615.34	0.00	221
$\Delta income_{suezmax}$	0.0018	0.0653	2.07	25.75	4,990.97	0.00	584.33	0.00	224
$\Delta supply_{suezmax}$	0.0032	0.0036	2.39	11.15	822.62	0.00	628.10	0.00	221
$\Delta income_{aframax}$	0.0017	0.0506	2.14	19.72	2,780.33	0.00	567.33	0.00	224
$\Delta supply_{aframax}$	0.0033	0.0030	1.41	4.63	97.86	0.00	632.41	0.00	221
$\Delta income_{panamax}$	0.0011	0.0701	4.19	52.26	23,304.47	0.00	712.40	0.00	224
$\Delta supply_{panamax}$	0.0026	0.0040	1.17	3.00	50.84	0.00	621.30	0.00	221
$\Delta income_{handysize}$	-0.0009	0.0956	1.38	54.73	25,051.88	0.00	561.77	0.00	224
$\Delta supply_{handysize}$	0.0022	0.0027	1.74	5.43	165.25	0.00	661.45	0.00	221
$\Delta fuel_{tanker}$	-0.0022	0.1131	-0.13	4.72	28.19	0.00	872.33	0.00	224
$\Delta income^{atlantic}_{capesize}$	-0.0025	0.1377	-1.32	41.70	12,165.35	0.00	934.24	0.00	194
$\Delta income^{pacific}_{capesize}$	-0.0009	0.1862	-0.44	26.95	4,641.63	0.00	933.21	0.00	194
$\Delta supply_{capesize}$	0.0009	0.0010	0.82	2.95	21.59	0.00	863.20	0.00	192
$\Delta fuel_{drybulk}$	0.0005	0.1146	-0.14	5.00	33.02	0.00	1,092.10	0.00	194

Table 3 reports descriptive statistics for the logarithmic returns of the income, fuel, and supply variables in the tanker and dry bulk markets, and for the different types of vessels. The results indicate that in the tanker market the mean income values for larger size vessels are higher than for smaller ones; whereas, for the dry bulk market the income is negative and larger in the Atlantic region than in the Pacific region. Unconditional volatilities (standard deviation) follow a similar pattern for VLCCs, Suezmaxes and Aframaxes. However, the pattern breaks for Panamaxes and Handysizes, where the volatility increases, and is highest for the smallest size vessels in the Handysize sector. The fuel variable mean magnitude differs, and its sign alters between the two markets, but this is due to the reduced sample period in the case of the dry bulk market. In terms of supply, we observe no large differences in the mean value for the three larger size vessels (VLLC, Suezmax, Aframax) and this is reduced for the smaller size ones (Panamax, Handysize). The Jarque and Bera (1980) test indicate significant departures from normality for all variables, and the Ljung and Box (1978) Q statistic for 10th-order autocorrelations reveal that serial correlation is present in all cases.

Since the series are all I (1), we test for the presence of cointegration to verify the existence of a long-run relationship between them. Table 4 presents the results of the Johansen and Juselius (1990) test for cointegration. This approach overcomes the well-known limitations of the Johansen (Johansen, 1988, 1991) approach in small samples and offers the further advantage of allowing non-normal and conditional heteroskedastic innovations (Gonzalo 1994, Cheung and Lai 1993), so it is more appropriate for our data. Evidence from both trace and maximal eigenvalue tests, reported in Table 4, suggests that there is at most a single cointegrating vector or two common stochastic trends in all segments at 5% significance level. The lag length is chosen using the SBIC information criterion (Schwarz, 1987). The results are invariant to minor modifications of the lag length, supporting the conclusion of a single cointegrating vector. Since the Maximum Likelihood estimator may be biased in small samples, estimation of the testing equations is also performed with the dynamic OLS(DOLS) of Stock and Watson (1993) (results are available upon request by the authors). The two sets of estimates are very similar, confirming robustness of our conclusions. Finally, the scaling-up factor on the asymptotic critical values of the trace test suggested by Cheung and Lai's (1993) the does not alter our conclusion of cointegration rank, further strengthening our conclusion of the existence of one cointegrating relationship.

Table 4. Results of Johansen and Juselius cointegration test

Segments	Lags	Hypothesis		Test Statistics	
		H_0	H_A	λ_{max}	λ_{trace}
VLCC	1	$r = 0$	$r \geq 0$	68.36[b]	215.64[b]
		$r \leq 1$	$r > 1$	43.78	147.32
		$r \leq 2$	$r > 2$	23.45	70.43
Suezmax	1	$r = 0$	$r \geq 0$	75.33[b]	206.84[b]
		$r \leq 1$	$r > 1$	40.20	120.45
		$r \leq 2$	$r > 2$	21.33	69.33
Aframax	1	$r = 0$	$r \geq 0$	65.54[b]	243.56[b]
		$r \leq 1$	$r > 1$	34.21	121.83
		$r \leq 2$	$r > 2$	22.12	65.42
Panamax	1	$r = 0$	$r \geq 0$	83.21[b]	217.62[b]
		$r \leq 1$	$r > 1$	40.01	109.65
		$r \leq 2$	$r > 2$	21.76	66.32
Handysize	1	$r = 0$	$r \geq 0$	79.08[b]	211.56[b]
		$r \leq 1$	$r > 1$	42.65	109.02
		$r \leq 2$	$r > 2$	25.34	60.45

Capesize (A)	1	$r = 0$	$r \geq 0$	76.33 [b]	215.32 [b]
		$r \leq 1$	$r > 1$	40.03	98.33
		$r \leq 2$	$r > 2$	36.55	60.45
Capesize (P)	1	$r = 0$	$r \geq 0$	65.03 [b]	66.75 [b]
		$r \leq 1$	$r > 1$	38.50	40.01
		$r \leq 2$	$r > 2$	19.04	22.03

The table reports the results of the Johansen Juselius MLE tests for multiple cointegrating vectors. The optimal lag structure for each of the VAR models was selected by minimizing the SBIC's information criteria. In the final analysis, we use a lag of 1 Critical values used are sourced from Osterwald-Lenum (1992) and a comparison is made to that reported by Cheung and Lai (1993) for small sample bias, b indicates rejection at the least at the 95% critical values.

Finally in order to test that each of the variables enter the cointegrating vector significantly, we test for zero restrictions upon each of the coefficients derived by the Johansen procedure. Coefficient estimates and significance levels associated with the tests of zero-loading restrictions appear in the last column of Table 4. Normalizing the income coefficient in the cointegrating equation, the significance levels provide evidence of each of these restrictions being rejected for all segments at 99% significance level. This implies that all variables enter into the cointegrating vector at a statistically significant level and adjust significantly to clear any short-run disequilibrium.

3.3. Vector Error Correction Model

In presence of cointegration, a Vector Error Correction Model (VECM) can be specified to identify the nature of the long-run and short-run relationships between the variables of interest. Using a model based on the difference variables only may imply loss of information on linkages displayed purely over the long run which may provide useful for financial analysts and investors. Engle and Granger (1987) show that in the presence of cointegration, there always exists a corresponding error–correction representation. This implies that changes in the dependent variable are a function of the level of disequilibrium in the cointegrating relationship (captured by the error–correction term), as well as changes in other explanatory variables. The model equations are defined as:

$$\Delta income_{j,t} = \alpha_{01} + \sum_{i=1}^{q} \alpha_{1,i}\Delta income_{j,t-i} + \sum_{i=1}^{q} \beta_{1,i}\Delta fuel_{t-i} + \sum_{i=1}^{q} \delta_{1,i}\Delta supply_{j,t-i} + \gamma_1\big(income_{j,t-i} + \theta_1 fuel_{t-i} + \theta_2 supply_{j,t-i} + \theta_{01} + \theta_{02}\big) + \varepsilon_{1,t}, \quad \text{(Eq. 4)}$$

$$\Delta fuel_{t} = \alpha_{02} + \sum_{i=1}^{q} \alpha_{2,i}\Delta income_{j,t-i} + \sum_{i=1}^{q} \beta_{2,i}\Delta fuel_{t-i} + \sum_{i=1}^{q} \delta_{2,i}\Delta supply_{j,t-i} + \gamma_2\big(income_{j,t-i} + \theta_1 fuel_{t-i} + \theta_2 supply_{j,t-i} + \theta_{01} + \theta_{02}\big) + \varepsilon_{1,t}, \quad \text{(Eq. 5)}$$

$$\Delta supply_{j,t} = \alpha_{03} + \sum_{i=1}^{q} \alpha_{3,i}\Delta income_{j,t-i} + \sum_{i=1}^{q} \beta_{3,i}\Delta fuel_{t-i} + \sum_{i=1}^{q} \delta_{3,i}\Delta supply_{j,t-i} + \gamma_3\big(income_{j,t-i} + \theta_1 fuel_{t-i} + \theta_2 supply_{j,t-i} + \theta_{01} + \theta_{02}\big) + \varepsilon_{1,t}, \quad \text{(Eq. 6)}$$

The short-run dynamics are captured by the coefficients of the differenced variables and the term in brackets, $\big(income_{j,t-i} + \theta_1 fuel_{t-i} + \theta_2 supply_{j,t-i} + \theta_{01} + \theta_{02}\big)$, is the error correction term (ECT) which represents the cointegrating (long-run) relationship between the series. The parameters γ_i measure the speed of adjustment of the series to the long run equilibrium. The model permits inference on both short run and long run linkages. Specifically, in the short-run, the VECM framework allows to test for Granger causality among variables. The most popular test of Granger causality in cointegrated VAR with I(1) variables is the Johansen (1988,1991) test. The test is robust to some extent to the presence of non-normality and heteroskedasticity (Cheung and Lai, 1993), even if it suffers from small sample bias (Toda, 1995) and it relies on preliminary testing of cointegration. Results are reported in Table 3.

5. Temporal causality results based on vector error-correction model.

F-statistics														
ΔI_{vlcc}	ΔS_{vlcc}	ΔI_S	ΔS_S	ΔI_A	ΔS_A	ΔI_P	ΔS_P	ΔI_H	ΔS_H	ΔF_T	ΔI_C^A	ΔI_C^P	ΔS_C	ΔF_D
-	1.85*	-	-	-	-	-	-	-	-	1.95*	-	-	-	-
3.78***	-	-	-	-	-	-	-	-	-	2.34**	-	-	-	-
-	-	-	1.83*	-	-	-	-	-	-	0.256	-	-	-	-
-	-	3.51***	-	-	-	-	-	-	-	1.83*	-	-	-	-
-	-	-	-	-	0.395	-	-	-	-	0.432	-	-	-	-
-	-	-	-	1.67*	-	-	-	-	-	0.883	-	-	-	-
-	-	-	-	-	-	-	1.78*	-	-	1.86*	-	-	-	-
-	-	-	-	-	-	3.86***	-	-	-	1.88*	-	-	-	-

-	-	-	-	-	-	-	-	-	2.89**	1.90*	-	-	-	-
-	-	-	-	-		-	-	3.85***	-	1.92*	-	-	-	-
1.83*	3.88**	4.88***	1.92*	0.986	1.87**	5.43***	0.457	2.77**	1.87*	-	-	-	-	-
-	-	-	-	-	-	-	-	-	-	-	-	-		
-	-	-	-	-	-	-	-	-	-	-	-	-	1.95*	2.85**
-	-	-	-	-	-	-	-	-	-	-	4.56***	3.82***	-	1.97*
-	-	-	-	-	-	-	-	-	-	-	-	1.82*	2.87**	-

For brevity and to accommodate all data in one table, ΔI_{vlcc}, ΔS_{vlcc}, ΔI_S, ΔS_S, ΔI_A, ΔS_A, ΔI_P ΔS_P, ΔI_H, ΔS_H, ΔF_T, ΔI_C^A, ΔI_C^P, ΔS_C, ΔF_D,
e_{vlcc}, $\Delta supply_{vlcc}$, $\Delta income_{suezmax}$, $\Delta income_{aframax}$, $\Delta income_{panamax}$, $\Delta supply_{panamax}$,
$e_{handysize}$, $\Delta supply_{handysize}$, $\Delta fuel_{tanker}$, $\Delta income_{capesize}^{atlantic}$, $\Delta income_{capesize}^{pacific}$, $\Delta supply_{capesize}$, $\Delta fuel_{drybulk}$.
T was derived by normalizing the cointegrating vector on Income, with the residual checked for stationarity via unit root tests and inspection of it
presented in the final column are estimated t-statistics testing the null that the lagged ECT is statistically insignificant for each equation. All other es
mptotic Granger F-statistics. The VECM was estimated including an optimally determined (SBIC) lag structure of 4 for all lagged-difference terr
ons and a constant. a, b and c indicate significance at the 1, 5 and 10% levels

4. Results and Discussion

The estimation results in Tables 6a and 6b suggest that the model can capture a large fraction of the variation in the income, fuel, and supply variables since all adjusted R-squared values are above 80%, with most approaching 90%.

Furthermore, all gamma coefficients (Column $\gamma = 1, 2, 3$) are small in magnitude and statistically significant, indicating an adequate specification of the VECM model. Their negative signs imply that, when there is a positive (negative) deviation from the long-run equilibrium, the respective variable(s) will decrease (increase) in order to revert to it. For example, the income premium is expected to decrease following an increase in the previous period. Post estimation diagnostic tests

Both fuel and supply are statistically significant in explaining the income premium (Equation 4; Column $\Delta income_{j,t}$) in each segment, with the coefficients' signs being in line with economic theory. Namely, when the fuel variable increases, that is the more expensive it becomes to pay for VLSFO compared to HSFO, charterers are willing to pay relatively more to lease a scrubber-fitted vessel since it will substantially reduce their fuel costs. Furthermore, when the size of the scrubber-fitted fleet increases, the income premium decreases. The reason is that there is relatively more supply to accommodate the charterers' needs for such vessels. The coefficient of the income variable is much smaller in magnitude, suggesting that changes in the fuel and supply variables have much stronger effects on income compared to its past values.

Interestingly, while the signs and significance of the fuel and supply coefficients in the long run (i.e. θ_1 and θ_2) are consistent with the ones in the short run, the magnitudes change. On the one hand, as installing a scrubber is a long-term investment decision, which affects not only the specific vessel but the aggregate fleet too, it has much a stronger effect on the income premium in the longer horizon. On the other hand, while fluctuations in the fuel spread significantly affect the income premium in the short horizon, as they determine the charterers' costs, the effect diminishes in the long run. In line with this argument and the high volatility of the fuel variable (Figure 1), the coefficient of fuel in Equation 5 is significantly below 0.5 across all segments, suggesting a relatively low persistence of the variable even in the short run.

These results have important industry implications as they provide strong statistical evidence about the relationship between TC rates, fuel prices, and the supply of the fleet and, thus, a framework to interpret how changes in one variable will affect the other. Indicatively, if the fuel spread increases by 1%, owners and charterers of VLCC vessels can expect a roughly 0.85% increase in the income premium in the next week, ceteris paribus. Or, if the fleet has increased by 1%, the income premium is expected to roughly decrease by -1.07% in the subsequent period, other things equal. This, in turn, can inform companies' chartering policies while VLCC brokers can incorporate that information in their assessments of the future TC rates and advise their clients accordingly.

Table 6a. Results of VECM (Tanker Market)

$$\Delta income_{j,t} = \sum_{i=1}^{q} a_i \Delta income_{j,t-i} + \sum_{i=1}^{q} a_i \Delta fuel_{t-i} + \sum_{i=1}^{q} a_i \Delta supply_{j,t-i} + \gamma_1 (income_{j,t-i} + \theta_1 fuel_{t-i} + \theta_2 supply_{j,t-i} + \theta_{01} + \theta_{02}) + \varepsilon_{1,t} \quad \text{(Eq. 4)}$$

$$\Delta fuel_t = \sum_{i=1}^{q} a_i \Delta income_{j,t-i} + \sum_{i=1}^{q} a_i \Delta fuel_{t-i} + \sum_{i=1}^{q} a_i \Delta supply_{j,t-i} + \gamma_2 (income_{j,t-i} + \theta_1 fuel_{t-i} + \theta_2 supply_{j,t-i} + \theta_{01} + \theta_{02}) + \varepsilon_{1,t} \quad \text{(Eq. 5)}$$

$$\Delta supply_{j,t} = \sum_{i=1}^{q} a_i \Delta income_{j,t-i} + \sum_{i=1}^{q} a_i \Delta fuel_{t-i} + \sum_{i=1}^{q} a_i \Delta supply_{j,t-i} + \gamma_3 (income_{j,t-i} + \theta_1 fuel_{t-i} + \theta_2 supply_{j,t-i} + \theta_{01} + \theta_{02}) + \varepsilon_{1,t} \quad \text{(Eq. 6)}$$

Estimated Model					Cointegrating equation				
$\gamma = 1,2,3$	$\Delta income_{j,t}$	$\Delta fuel_t$	$\Delta supply_{j,t}$	$\bar{R}^2$	[1	θ_1	θ_2	θ_{01}	θ_{02}]

j = **VLCC**					0.896	[1	0.0658^{a} (0.000)	-2.3278^{a} (0.001)	-0.0058	1.7496]
$\Delta income_{j,t-1}$	-0.0012^{a} (0.000)	0.0234^{c} (0.061)	0.9918^{b} (0.038)	0.0010^{c} (0.055)						
$\Delta fuel_{t-1}$	-0.0051^{b} (0.001)	0.8516^{a} (0.007)	0.3507^{c} (0.087)	0.003^{b} (0.028)						
$\Delta supply_{j,t-4}$	-0.0019^{a} (0.003)	-2.0348^{a} (0.008)	-1.0683^{b} (0.034)	- 0.0028^{c} (0.076)						
j = **Suezmax**					0.873	[1	0.0593^{a} (0.005)	-3.8787^{a} (0.001)	-0.0016	0.6685]
$\Delta income_{j,t-1}$	-0.0075^{a} (0.008)	0.0359^{b} (0.007)	0.9566^{b} (0.030)	0.0057^{b} (0.035)						
$\Delta fuel_{t-1}$	-0.0603^{b} (0.035)	0.7019^{c} (0.061)	0.3560^{a} (0.008)	0.0006^{b} (0.041)						
$\Delta supply_{j,t-4}$	-0.0012^{a} (0.005)	-3.8062^{a} (0.007)	-1.8846^{a} (0.001)	-0.0039^{c} (0.068)						
j = **Aframax**					0.810	[1	0.0604^{c} (0.052)	- 5.1945^{c} (0.076)	-0.0006	0.1194]
$\Delta income_{j,t-1}$	-0.0043^{a} (0.006)	0.1365^{c} (0.067)	0.2156^{c} (0.074)	0.0002^{c} (0.074)						
$\Delta fuel_{t-1}$	-0.0073^{b} (0.045)	0.3920^{a} (0.007)	0.3735^{b} (0.041)	0.0023^{b} (0.021)						
$\Delta supply_{j,t-4}$	-0.0010^{c} (0.071)	-2.4557^{a} (0.003)	-0.9782^{b} (0.050)	-0.0032^{a} (0.063)						
j = **Panamax**					0.894	[1	0.0319^{a} (0.001)	-2.7158^{a} (0.008)	-0.0007	0.0793]
$\Delta income_{j,t-1}$	-0.0061^{a} (0.004)	0.0241^{c} (0.057)	0.3672^{b} (0.045)	0.0002^{b} (0.030)						
$\Delta fuel_{t-1}$	-0.0092^{b} (0.03)	0.9211^{b} (0.033)	0.3507^{a} (0.009)	0.0003^{b} (0.046)						
$\Delta supply_{j,t-4}$	-0.0095^{a} (0.005)	-1.4419^{a} (0.007)	-0.9272^{b} (0.037)	-0.0012^{c} (0.076)						
j = **Handysize**					0.889	[1	0.0014^{a} (0.008)	-4.6173^{a} (0.000)	-0.0018	1.2819]
$\Delta income_{j,t-1}$	-0.0072^{a} (0.009)	0.0337^{c} (0.071)	0.7389^{c} (0.076)	0.0002^{c} (0.054)						
$\Delta fuel_{t-1}$	-0.0058^{a} (0.001)	0.9948^{b} (0.031)	0.3730^{c} (0.075)	0.0003^{b} (0.035)						
$\Delta supply_{j,t-4}$	-0.0064^{b} (0.015)	-2.5148^{a} (0.001)	-1.0034^{c} (0.062)	0.0016^{c} (0.073)						

Superscripts a, b, and c denote significance at the 1, 5, and 10 percent level, respectively. Values in (.) are standard errors.

Table 6b. Results of VECM (Dry Bulk Market)

$$\Delta income_{j,t} = \sum_{i=1}^{q} a_i \Delta income_{j,t-i} + \sum_{i=1}^{q} a_i \Delta fuel_{t-i} + \sum_{i=1}^{q} a_i \Delta supply_{j,t-i} + \gamma_1 (income_{j,t-i} + \theta_1 fuel_{t-i} + \theta_2 supply_{j,t-i} + \theta_{01} + \theta_{02}) + \varepsilon_{1,t} \quad \text{(Eq. 4)}$$

$$\Delta fuel_{t} = \sum_{i=1}^{q} a_i \Delta income_{j,t-i} + \sum_{i=1}^{q} a_i \Delta fuel_{t-i} + \sum_{i=1}^{q} a_i \Delta supply_{j,t-i} + \gamma_2 (income_{j,t-i} + \theta_1 fuel_{t-i} + \theta_2 supply_{j,t-i} + \theta_{01} + \theta_{02}) + \varepsilon_{1,t} \quad \text{(Eq. 5)}$$

$$\Delta supply_{j,t} = \sum_{i=1}^{q} a_i \Delta income_{j,t-i} + \sum_{i=1}^{q} a_i \Delta fuel_{t-i} + \sum_{i=1}^{q} a_i \Delta supply_{j,t-i} + \gamma_3 (income_{j,t-i} + \theta_1 fuel_{t-i} + \theta_2 supply_{j,t-i} + \theta_{01} + \theta_{02}) + \varepsilon_{1,t} \quad \text{(Eq. 6)}$$

Estimated Model	Cointegrating equation

	$\gamma = 1,2,3$	$\Delta income_{j,t}$	$\Delta fuel_{j,t}$	$\Delta supply_{j,t}$	$\bar{R}^2$	[1	θ_1	θ_2	θ_{01}	θ_{02}]
j = Capesize (Atlantic)					0.893	[1	0.8762[b] (0.042)	-3.7820[b] (0.039)	-0.0020	0.4584]
$\Delta income_{j,t-1}$	-0.0386[a] (0.005)	0.0752[c] (0.078)	0.0567[c] (0.090)	0.0052[c] (0.065)						
$\Delta fuel_{t-1}$	-0.0052[b] (0.011)	1.6048[a] (0.006)	0.2482[c] (0.068)	0.0033[c] (0.070)						
$\Delta supply_{j,t-4}$	-0.0043[a] (0.003)	-2.6530[a] (0.005)	-0.5630[c] (0.078)	-0.0022[c] (0.081)						
j = Capesize (Pacific)					0.882	[1	0.6791[a] (0.001)	-3.9716[a] (0.001)	-0.0059	0.7893]
$\Delta income_{j,t-1}$	-0.0043[a] (0.000)	0.3125[c] (0.083)	0.0630[c] (0.065)	0.0014[c] (0.080)						
$\Delta fuel_{t-1}$	-0.0004[a] (0.008)	1.1772[b] (0.038)	0.1870[c] (0.052)	0.0027[c] (0.065)						
$\Delta supply_{j,t-4}$	-0.0071[a] (0.009)	-2.5910[a] (0.007)	-0.6920[b] (0.040)	-0.0045[c] (0.085)						

Superscripts a, b, and c denote significance at the 1, 5, and 10 percent level, respectively. Values in (.) are standard errors.

Practitioners and policy makers alike have raised concerns regarding the current and future price differential between VLSFO and HSFO and whether there will be sufficient supply of both fuels in the future to accommodate the needs of the maritime industry. On the one hand, there is the view that HSFO, being the conventional and less refined fuel, will remain available for vessel bunkering. The opposing view is that, with the increasing need for VLSFO, the spread between the two will gradually diminish, VLSFO will become the conventional fuel oil, and major ports will only supply this in the future. For the time being, all major bunkering locations, including Singapore, Rotterdam, Gibraltar, Fujairah, supply both fuels. In case the supply of HSFO reduces in the future though, scrubber-fitted vessels will have to pre-order their bunkers or deviate from their route for bunkering. This may reduce profitability and create disputes between owners and charterers.

The results from Equation 5 (Column $\boldsymbol{\Delta fuel_t}$) help shed light on that question. Namely, the coefficient of the supply variable is significantly negative across all segments, suggesting that, as the supply of the scrubber-fitted fleet increases, the fuel spread decreases. This is because an increasing number of such vessels is associated with higher demand for HSFO relative to VLSFO which, ceteris paribus, results in a decrease in the fuel spread. The magnitude of the coefficient is close to or above 1 irrespective of the segment, indicating that there is a strong effect in the short run. Due to the time required to retrofit or build a new vessel though, the relative supply of the fleet changes much more slowly than the income and fuel spreads (as indicated by the standard deviations in Table X). Consequently, the effect of the supply variable on the fuel spread becomes stronger in the long run.

The relatively low coefficient of the fuel variable, along with its large standard deviation (Tables 6a and 6b), further indicate the high volatility of the fuel spread. The coefficient of the income variable is positive and significant in all cases. When the premium required to charter a scrubber-fitted vessel has increased, charterers become keener to explore the alternative option of employing a non-scrubber-fitted vessel. As the latter burns VLSFO though, the higher demand for it drives the fuel spread up. However, it is important to note that the magnitude of the supply coefficients is (much) larger than the income and fuel ones across all segments.

As discussed above, scrubbers have certain limitations that may deter vessel owners from equipping their vessels with one: the associated capital and operating expenditure; the off-hire period during the retrofit; and challenges regarding the installation process and the scrubber operation per se. Panasiuk et al. (2016) suggest that the scrubber installation impacts a vessel's stability, deadweight, trim, heel, and keel. Thus, its exact location of installation on a vessel is crucial to optimise its efficiency and effectiveness.

Therefore, it is important to examine the factors that affect shipowners' decision to install a scrubber. Note that, since installing a scrubber takes considerable time, the fourth lag of the right-hand-side variables is incorporated in Equation 6 – instead of the first lag which is the case in Equations 4 and 5. The results are robust to different lag specifications though.

The findings suggest that both the income and fuel variables are positively and significantly related to the size of the scrubber-fitted fleet. As the TC income from scrubber-fitted vessels increases compared to non-scrubber-fitted ones', it becomes more financially attractive to install a scrubber. This is also the case when the VLSFO price rises relative to the HSFO one for two reasons. If the shipowner operates the vessel in the spot market, their fuel costs substantially decrease by burning HSFO instead of VLSFO. If instead the vessel is leased out in a TC contract, while the shipowner does not incur the fuel cost, the scrubber option becomes more attractive to potential charterers as it largely reduces their fuel costs.

Moreover, the supply of scrubber-fitted vessels negatively affects the future size of the respective fleet. As more vessels become equipped with a scrubber, the shipowner might perceive that there is less residual demand for those by charterers but also that the resulting increased demand for HSFO could reduce the availability of the fuel and raise its price compared to VLSFO. Namely, if HSFO has limited availability in certain ports, it might be worthwhile for shipowners (and charterers) to purchase in bulk

VLSFO for their (chartered) fleet to ensure smooth supply chain operations, instead of incurring the capital expenditure to install a scrubber and potentially make their vessels less competitive.

Note that the magnitude and significance of the three coefficients is much smaller in the supply equation compared to the income and fuel ones. For example, in the VLCC case, a 1% increase in the TC premium results in a 0.001% rise in the future size of the scrubber-fitted fleet, ceteris paribus; a 1% increase in the fuel spread, in a 0.03% rise in the future scrubber-fitted fleet, ceteris paribus; and a 1% increase in the supply, in a 0.003% decrease in the future scrubber-fitted fleet, ceteris paribus. This is because, on the one hand, a long-term decision as the installation of a scrubber, does not only depend on the fuel and TC conditions at one point in time and, on the other hand, an e.g. 0.003% change in the fleet is rather large in magnitude.

On the relevance of shipping decarbonisation, our results provide strong evidence that green investment and market uncertainty are mutually dependent. The decision to invest in green initiatives is influenced by foreseeable future income, which in turn is affected by the number of first movers undertaking green investments. Many scholars argue that market uncertainty has an adverse effect on promoting green investment (……..), but we propose that green investment itself may also cause market uncertainty. Our analysis documents that an increase in the fleet size of scrubber-fitted vessels reduces their future income, as both the TC premium and fuel spread decrease.

Those results have significant industry and policy implications. Industry participants shall evaluate a green investment based on at least three factors: a) the projected future income; b) the availability of green fuel; c) their competitors' decisions. Since the TC premium and fuel spread directly affect the shipowner's profit in the spot and TC market, respectively, the significance and sign of the associated coefficients showcase the importance of the relative financial performance of the vessel in the decision to install a scrubber. The negative sign and significance of the supply coefficient suggest that the size of the scrubber-fitted fleet and concerns about future limited availability of HSFO might deter shipowners from installing a scrubber.

From a policy perspective and in the wider context of shipping sustainability, the findings suggest that the interrelation between market uncertainty and green investment may further delay the progress of shipping decarbonisation. Market uncertainty poses risks to investors in green shipping. In addition, a high supply of green investments mitigates their financial benefits for investors. Unless shipping investors have clear financial incentives, they will not undertake green investments. Furthermore, clarity about the future availability of the respective fuels and resilience in terms of bunkering and the wider supply chains are also key factors to ensure a smooth transition towards net zero shipping.

5. Conclusion

The installation of a scrubber can be considered as a hedge against future uncertainty with respect to operational and financial costs, which can be reduced if a scrubber is installed. Conclusions

Since the start of 2020, vessel owners are faced with a dilemma in order to abide by the sulphur cap introduced by the International Maritime Organization. The dilemma at hand is whether to retrofit a large vessel with a scrubber system or switch to a more expensive fuel with 0.5% sulphur content or less.

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