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Determinants of the price premium for eco vessels

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Abstract

Shipping companies face the trilemma of investing in cheaper but more polluting conventional vessels, in more expensive but eco-friendly ones or postponing their investment. We quantify the price premium paid for eco-friendly vessels and investigate its determinants. The results indicate that eco vessels trade at an average premium of 25% compared to their conventional counterparts, while the corresponding income premia are between 9% and 15%. Our findings further suggest that the price premium depends on the market conditions, with income premia, past price premia, and fleet supply being strong drivers, while fuel costs and market liquidity have a less important effect. The magnitude and significance of these drivers vary based on the market state and segment. Overall, the paper documents the adverse effect that the current technological and regulatory uncertainty has on vessel investment and highlights the need for further policy intervention to reduce market uncertainty and encourage green investment.

Keywords: Asset Pricing; Sustainable Shipping; Maritime Decarbonisation; Vessel Prices; Net Zero Shipping; Price Premium

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I. Introduction

Shipping facilitates over 80% of global trade (UNCTAD, 2021), with world seaborne trade, measured in tonne-nautical miles, increasing at an average rate of 3.3% since 2000 (Clarksons' SIN, 2024). While shipping is less polluting per transport work (i.e. tonne-nautical mile) compared to other transport modes, due to the scale of its operations, it accounts for 2.8% of global greenhouse gas (GHG) emissions (UNCTAD, 2023). In other words, if global shipping were a country, it would be the sixth largest carbon dioxide (CO₂) emitter in the world (Statista, 2023). Without any further action, shipping CO₂ emissions are expected to increase by 90-130% by 2050 compared to the 2008 levels (IMO, 2018).

As a result, shipping environmental regulations are becoming increasingly strict. The International Maritime Organization's (IMO) Initial Greenhouse Gas Strategy was "aiming at reducing CO₂ emissions from vessels by at least 40% by 2030, pursuing efforts towards 70% by 2050, vis-à-vis 2008 levels" (IMO, 2018). However, the revised and more ambitious 2023 IMO GHG Strategy aims at peaking "GHG emissions from international shipping as soon as possible and reaching net-zero by or around 2050." Furthermore, it "targets to reduce CO₂ emissions per transport work, as an average across international shipping, by at least 40% by 2030, compared to 2008" (IMO, 2023).

To achieve that, among other measures, the shipping industry has recently started utilising vessels that are more eco-friendly—in terms of reduced fuel consumption and, in turn, CO₂ emissions—compared to conventional ones. While we acknowledge the wide range of emissions from shipping—such as sulphur oxide (SO_x), nitrous oxide, and methane—this paper focuses on CO₂ emissions as those account for roughly 98% of the total shipping greenhouse gases (GHGs) and, thus, have been the main focus of the international regulatory agenda.

As such, ship owners have been facing the trilemma of investing in a cheaper but much more polluting (in terms of emissions) conventional vessel, or in a more expensive but eco-friendly one, or postponing their investment decision. Traditionally, the primary investment risk had to do with market volatility, that is when it is the right time to invest based on the prevailing and expected freight market conditions. In the last years though, there is also a technological risk related to the uncertainty regarding the optimal fuel choice and the technological specifications of a newly ordered or purchased vessel. This, in turn, depends on the cost of fuel production; the availability and price of the fuel; the required technology for the vessel to burn that fuel; safety concerns; regulations (which can vary among jurisdictions); market-based measures as a potential carbon levy; and the development of emissions trading systems (ETS) as the EU ETS (Financial Times, 2024).

From a technological perspective, eco-friendly vessels should trade at a price premium compared to their conventional (i.e. non-eco) counterparts. From a financial perspective though, for an investor to be willing to pay for such premium and for a capital provider (e.g. banks and hedge funds) to finance such acquisition, the eco vessel must generate higher cash flows or/and have a lower cost of capital than the conventional one. Consequently, our central research question is: does the shipping market, and individual segments within it, provide financial incentives towards shipping decarbonisation? A simplified version of this question, similar to the one posed by Thanopoulou and Tamvakis (2000), would be "does quality pay"? Intuitively, the answer to this question should be "yes", i.e. the higher price of eco-vessel should be justified by higher cash inflows and/or lower financing cost. However, complexities may exist, if the shipping market does not pass the benefits of shipping decarbonisation

to investors and there exist split incentives between financiers, ship owners, and charterers (Rehmatulla and Smith, 2020).

To this end, this paper investigates whether there is any price premium paid for eco-friendly cargo-carrying vessels, what are the main determinants of such premium, and whether shipping decarbonisation is encouraged by economic and financial incentives (in the form of higher freight rates and asset values, lower cost of capital, and other widely used financial variables), rather than being solely driven by international regulation. While we discuss about the impact of technologies and regulations on eco-vessel investment, the empirical analysis focuses on the financial perspective. We direct our attention to the dry bulk and crude oil tanker segments which, combined, are responsible for the transportation of more than three quarters of the world seaborne trade (Clarksons' SIN, 2024). More specifically, we focus on Capesize vessels on the dry bulk side and Aframax vessels on the tanker side. Both are larger vessel sizes, which are more likely to justify the investment in eco-friendly technologies and for which data were either directly available or were more straightforward to obtain.

From a science policy perspective, this study extends the knowledge framework of environmental policy to the shipping industry. To date, the literature has analysed the determinants of green technology in various fields, e.g. automobiles (Aghion et al., 2016), building construction (Noailly, 2012), manufacturing (Brunnermeier and Cohen, 2003), and water management (Conway et al., 2015). Nevertheless, there is a large gap in the literature regarding the economic and financial aspects of shipping sustainability (Bouman et al., 2017). Chen et al. (2018) and Psaraftis (2019) have focused on the technological and regulatory challenges related to sustainable shipping and Wang et al. (2023) on providing a theoretical discussion about the green developments in the industry. Moreover, a large body of the shipping literature has investigated alternative marine fuels, e.g., the relevant regulations of alternative fuels (Christodoulou and Cullinane, 2022; Dettner and Hilpert, 2023), the alternative fuel supply chain (Yang and Lam, 2023), and alternative fuel power systems (Chen and Lam, 2022). There is also a growing body of literature (Atrium, 2024; Mackenzie et al., 2024a, 2024b) examining the implications of environmental regulations on marine insurance. Gore et al. (2022) assess the cost effectiveness of alternative fuels and Zhang et al. (2021) investigate how the IMO 2020 sulphur cap influences ship owners' decisions on either installing SOx scrubbers (i.e. exhaust gas cleaning systems) or using low sulphur fuels. However, to the best of our knowledge, no research so far has explored eco-vessel investment from a financial perspective. Apart from the environmental need to do so, this is of a particular importance given that the shipping industry features substantial capital costs, high market uncertainty, and long payback periods (Kalouptsi, 2014; Greenwood and Hanson, 2015).

There exists a vast body of literature examining the relationship between vessel prices, investment in vessels, and freight rates. Namely, Greenwood and Hanson (2015) suggest a behavioural asset pricing model that quantifies the effects of extrapolative beliefs and competition neglect on vessel prices, freight rates, and investment in vessels. Alizadeh et al. (2017) and Moutzouris and Nomikos (2020) also develop heterogeneous beliefs models to capture the price dynamics of vessels. Kalouptsi (2014) examines the effect that the time-to-build between the order and delivery of a newbuilding vessel can have on shipping investment and asset prices. Furthermore, several papers incorporate standard empirical asset pricing frameworks (e.g. using the regression models of Fama and French, 1988, and Cochrane, 2005) to investigate whether freight rates and/or returns can explain the movements in vessel prices (Alizadeh and Nomikos, 2003; Adland et al., 2006; Alizadeh and Nomikos, 2007; Moutzouris and Nomikos, 2019). However, by focusing on a single vessel type in terms of

technological specifications, none of the above articles examines the price differential between eco and conventional vessels.

The pronounced uncertainty in shipping can amplify the effects of path dependency and capital market failures in shipping innovation. Notably, our findings reveal that internal and systematic factors – such as cash flow premia, past vessel price premia, and fleet supply – exert a stronger impact than external factors – such as fuel costs, market liquidity, and cost of capital – on green technology adoption in shipping. This contrasts with findings in other green technology fields, where external factors are often strong determinants of energy technology adoption (Popp, 2002, 2019). One possible explanation is that path dependency makes it difficult for green technology to replace the existing technological system due to high switching costs. The other possible explanation is that the high financial, technological, and regulatory uncertainty, coupled with capital market failures (e.g. herd behaviour and risk aversion), magnify the influence of internal and systematic factors (Avery and Zemsky, 1998; Chronopoulos and Siddiqui, 2015).

Due to the transition towards net zero, green/sustainable finance is becoming increasingly important also in shipping. Namely, the Poseidon Principles “establish a framework for assessing and disclosing the climate alignment of shipping finance portfolios”, that is whether bank’s shipping investments align with the IMO’s targets for the reduction of GHGs (Poseidon Principles, 2023, 2024). They were officially launched in 2019, with eleven participating banks that represented more than \$100 million of shipping loans. In 2024, this has increased to 34 signatories representing approximately \$240 billion or 80% of the global ship finance portfolio (Poseidon Principles, 2023, 2024). Furthermore, shipping companies need to maintain a solid environmental, social, and governance (ESG) track record to be able to have access to either capital markets or syndicated loans, especially in Europe. According to our findings though, existing green finance debt rates do not seem able to justify the price differential between the eco and conventional vessels.

Our paper further contributes to the literature by providing an alternative model specification for the relationship between vessel prices and freight rates while controlling for various frequently incorporated shipping variables. Given that the price premium exhibits non-linear behaviour, driven by market conditions, we employ a threshold autoregressive model (Hansen, 2000) where the threshold is endogenously identified and the regime switching framework can capture any structural change, including policy related ones. This framework allows us to test and analyse the asymmetries in the relationship between eco price premia and its determinants and enables to examine whether the impact of those shipping variables varies between regimes, that is depending on the freight market conditions.

As such, we contribute to the shipping, asset pricing, and sustainable finance literature by investigating whether such eco price premium exists, quantifying it, and interpreting it. We also discuss and relate the empirical evidence to the aggregate investment in vessels and the provision of green capital and how this can affect the industry as a whole. Our findings also have policy implications: to promote investment and utilisation of eco-friendly vessels, stronger and clearer policy interventions are needed to further incentivise ship owners, charterers, and investors. This underscores the importance of further developing a clearly outlined plan for shipping decarbonisation in a timely manner. To the best of our knowledge, this is the first paper that explicitly examines shipping sustainability from this financial perspective and provides relevant recommendations.

The remainder of this paper is structured as follows. Section II describes the data and demonstrates some preliminary findings. Section III presents and motivates the empirical model and analyses the estimation results. Section IV further discusses the findings and their implications to the industry. Section V concludes.

II. Description of the Data

We consider economic and financial variables which directly affect the returns of a shipping investor, such as freight rates, vessel prices, and the cost of capital, but also additional economic factors related to the shipping market, i.e. fuel prices, market liquidity proxied by second hand vessel sales and fleet supply. We collect weekly data from Clarksons' Shipping Intelligence Network (SIN) and examine the price differential between eco-friendly and conventional vessels and its determinants.

The analysis and estimation focus on the dry bulk and tanker sectors which facilitate more than three quarters of the world seaborne trade (Clarksons' SIN, 2024). Specifically, it is performed for a representative vessel type from each of the two sectors, that is Capesize dry bulkers and Aframax tankers. Capesize vessels typically have a capacity of 180,000 deadweight tonnes and are mainly associated with the trades of iron ore, coal, and grains. Aframax vessels typically have a capacity of 115,000 deadweight tonnes and are involved with the transportation of oil (Clarksons' SIN, 2024). In line with the literature (e.g. Greenwood and Hanson, 2015; Moutzouris and Nomikos, 2019), we focus on second-hand (i.e. 5-year-old) vessels as opposed to newly ordered ones as the latter are not immediately available to operate in the market.¹ The sample period, given the limited data availability for eco-friendly vessels, ranges from 16 August 2019 to 30 December 2022 for Capesizes and from 4 January 2019 to 8 December 2023 for Aframax.

To examine the cost of capital dimension with respect to eco-vessel investment, we obtain data on standard loans, green loans (GLs) and sustainability-linked loans (SLLs) in shipping from Marine Money and Clarkson's SIN. Green loans provide financing for a specified project with environmental benefits, such as, alternatively fuelled newbuilding vessels, ballast water treatment, exhaust gas scrubbers, vessel efficiency improvements, and research and development programs (Houston, 2021). Sustainability-linked loans allow for proceeds to be used for general corporate purposes and are not required to directly generate sustainability benefits, if, shipping companies commit to certain Key Performance Indicators (KPIs) and set Sustainability Performance Targets (SPTs) (Houston, 2021). However, KPIs and SPTs may not be directly related to climate and the environment, but to health and safety of crew, gender diversity, and anti-corruption.

A sample of 69 shipping loans for the period 2020 to 2023 is collected from Marine Money and Clarksons' SIN. As illustrated in Figure 1, the spread differential between GLs/SLLs and standard loans is only 23 basis points. Due to unavailability of sufficient data for shipping loans for those two sectors (as the obtained sample is for the overall industry), we have not included the cost of capital as an explanatory variable in the main model. However, due to the marginal spread differential, we do not expect this to have significant explanatory power over the eco price premium.

¹ There exists a construction lag or, equivalently, time-to-build between the order and delivery of newbuilding vessel that can vary from twelve months, when there exists shipbuilding capacity (normally during market troughs) to more than five years when all existing shipyard berths are occupied (normally during market peaks). This of course also depends on the type of vessel under construction as more complicated designs, as cruise ships, usually require more time to build.



Figure 1. Average spread (in basis points) of shipping loans, 2020-2023.

Source: Authors' calculations. Data are from Marine Money and Clarksons' SIN.

Based on the above, the following economic and financial variables are selected for the analysis of the eco-vessel price premia. We utilise data for the prices of eco-friendly, $EP_{t,j}$, and conventional, $CP_{t,j}$, second-hand vessels, at period t and sector j ;² the time-charter rates (TC) for eco-friendly, $ETC_{t,j,k}$, and conventional, $CTC_{t,j,k}$, second-hand vessels – where k denotes the duration of the contract, 6-month, 1-, 3-, and 5-year; $Fuel_t$ costs;³ the percentage change in the fleet $Supply_{t,j}$ in DWT terms, capturing the supply in the sector; and sales of second-hand vessels divided by the concurrent size of the fleet as a proxy for market liquidity, $LQ_{t,j}$. $Supply_{t,j}$ and $LQ_{t,j}$ are only available at a monthly frequency and, therefore, they are converted to weekly frequency using the Chow Lin filter.⁴

As Table 1 suggests, the eco-friendly vessel on average burns much less tonnes of fossil fuel per sailing day compared to the conventional one. Namely, the eco Capesize vessel's consumption is 10 and 11 tonnes per day lower when sailing laden (i.e. loaded with cargo) and ballast (i.e. not loaded with cargo), respectively, than the conventional one's. For the Aframax vessel, the corresponding figures are 8 and 7 tonnes per day. This has important economic and financial implications that are analysed in the subsequent sections.

To examine the price differential between eco and conventional vessels, we define the eco price premium, $PP_{t,j}$, and the TC premium, $TCP_{t,j,k}$, using the following formulas:

² In the absence of available observations for both 5-year-old and 10-year-old 'eco' Aframax tanker vessels, we firstly rely on information provided by Clarkson's Research that all second-hand prices for 5-year-old Aframax tankers are, by definition, for 'eco' tankers. Secondly, we use the second-hand price for 10-year-old Aframax vessel and calculate the differential between the two second-hand prices. This differential should reflect both the age difference between the two vessels and the 'eco'/'non-eco' differential. Thirdly, we disaggregate the two elements of the differential, by estimating the age differential, based on the current TC earnings differential (for which we have 'eco' and 'non-eco' data) for every week, accrued over 350 (operating) days every year, for five years (the age difference between the two vessels) and discounted at 8% (the shipping industry long-term average). Lastly, once we estimate the age differential, we deduct it from the full second-hand price differential; the remainder should then reflect the 'eco' premium, and the obtained price can then be used in the same way as that for the Capesize dry bulk vessel.

³ As the vessels in the analysis are non-scrubber-fitted, the prices of very low sulphur fuel oil (VLSFO) are used and calculated as the weekly average at three key bunkering locations, i.e. Houston, Rotterdam, and Singapore.

⁴ Applying the Chow-Lin filter allows to align with the frequency of the dependent and rest of the independent variables, ensuring a sample size large enough to handle nonlinearities (Hansen, 2000).

$$PP_{t,j} = \frac{EP_{t,j}}{CP_{t,j}} - 1 \quad (1)$$

$$TCP_{t,j,k} = \frac{ETC_{t,j,k}}{CTC_{t,j,k}} - 1 \quad (2)$$

Table 1. Vessel specifications for the Capesize and Aframax conventional and eco-friendly types.

Ship Type	Typical DWT	Age (years)	SOx Scrubber	Speed Laden (knots)	Speed Ballast (knots)	Consumption at Sea Laden (t/day)	Consumption at Sea Ballast (t/day)	Consumption in Port
Capesize								
Conventional	180,000	5	None	12	13	43	43	5 (t/day)
Eco-friendly	180,000	5	None	12	13	33	32	5 (t/day)
Aframax								
Conventional	115,000	5	None	12.5	12	38	31	100 (t gross)
Eco-friendly	115,000	5	None	12.5	12	30	24	100 (t gross)

Source: Clarksons' SIN (2024).

Table 2 summarises descriptive statistics for the price and TC premia for the Capesize and Aframax sectors. Evidently, price premia are significantly higher than the 1- and 5-year TC premia. For the Capesize vessels, the price premium is 23.2% while the TC ones are close to 9.0%. Similarly, for the Aframax vessels, the corresponding figures are 24.9% and approximately 15%. The results are similar for the 6-month and 3-year TC contracts. This implies that TC premia on their own cannot explain the observed price premia.

Furthermore, price premia seem to exhibit higher volatility than the TC ones, as illustrated by both the standard deviations and the ranges of those variables. This finding is of interest on its own as the existing shipping asset pricing literature finds that TC rates are relatively more volatile than vessel prices (Moutzouris and Nomikos, 2019). A potential explanation for this discrepancy is that those papers examine the price determinants of a single vessel type and not the price differential between the eco and non eco versions of the asset.

The above features are also demonstrated in Figure 2 which plots the price and TC premia for the Capesize vessel. The figure further suggests that price premia are time varying as, in the first part of the sample (i.e. from 16 August 2019 to 19 March 2021), they are 31.4% on average while, in the second part of the sample (i.e. from 26 March 2021 to 30 December 2022), they amount to 15.4%. Furthermore, it seems that price and TC premia follow similar patterns, that is when the former are high so are the latter and vice versa. For conciseness, the presented figures and statistics correspond to the Capesize sector. However, the patterns are similar for the Aframax sector.

Table 2. Descriptive Statistics for price and contract premia.

	$j = \text{Capesize}$			$j = \text{Aframax}$		
	$PP_{t,j}$	$TCP_{t,j,1}$	$TCP_{t,j,5}$	$PP_{t,j}$	$TCP_{t,j,1}$	$TCP_{t,j,5}$
Mean	23.2%	8.8%	9.1%	24.9%	15.2%	14.4%
St. Deviation	8.3%	3.4%	2.4%	12.0%	6.8%	9.7%
Median	22.9%	8.5%	8.6%	27.5%	14.3%	10.9%
Kurtosis	-1.61	-0.11	-0.03	-0.31	2.62	0.02
Skewness	0.03	0.70	0.61	-0.69	1.27	1.15
Range	28.0%	15.4%	12.0%	48.8%	33.8%	31.8%
Min	9.8%	3.7%	2.5%	-0.04%	4.4%	3.8%
Max	37.7%	19.0%	14.5%	0.45%	38.3%	35.6%
N	177	177	177	258	258	258

In line with the shipping asset pricing literature (e.g. Kalouptsi, 2024; Greenwood and Hanson, 2015, Moutzouris and Nomikos, 2020), the analysis in the subsequent sections is focused on 1-year TC rates. However, for robustness, we have also performed the empirical estimation using the 5-year TC rates and the results are similar.

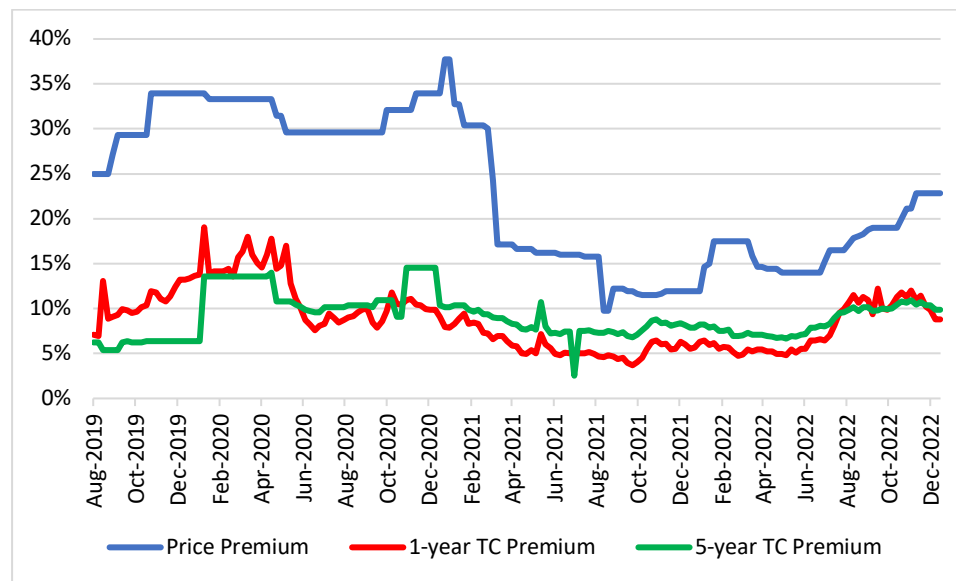


Figure 2. Price and 1- and 5-year time-charter premia for the Capesize sector.

Source: Authors' calculations. Data are from Clarksons' SIN.

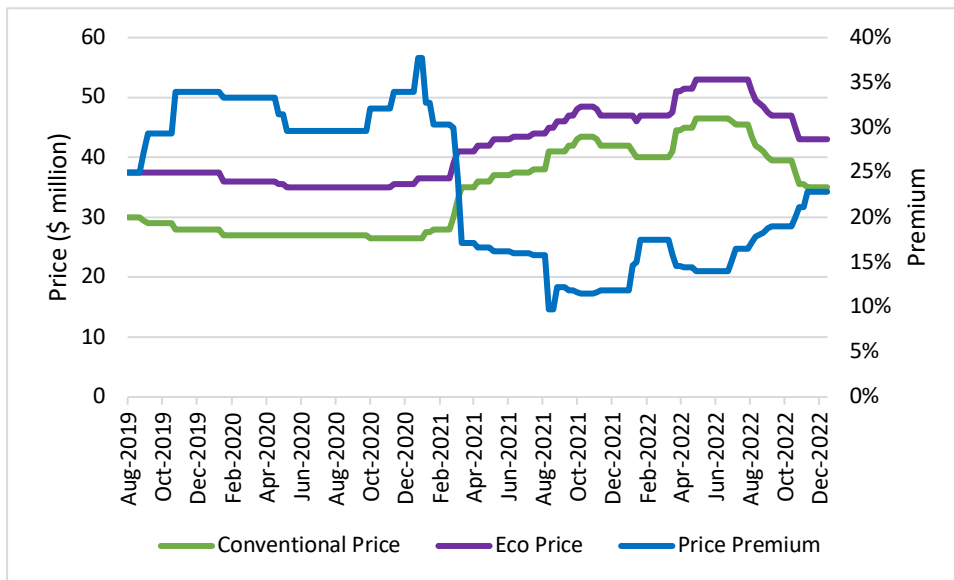


Figure 3. Price premium and eco-friendly and conventional vessel prices for the Capesize sector.
Source: Authors' calculations. Data are from Clarksons' SIN.

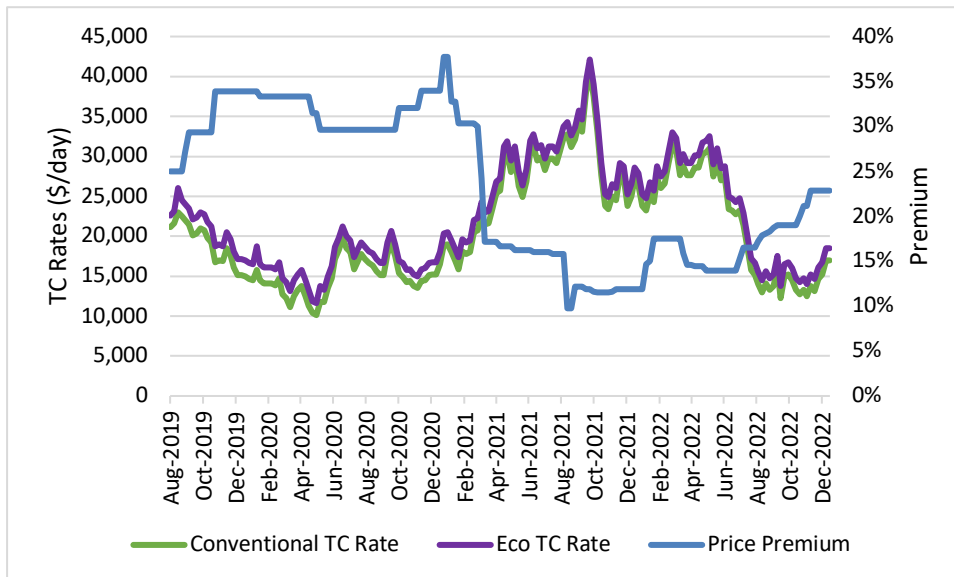


Figure 4. Price premium and eco-friendly and conventional TC rates for the Capesize sector.
Source: Authors' calculations. Data are from Clarksons' SIN.

To further examine the above stylised facts, Figure 3 plots the evolution of the Capesize price premium along with the prices for the eco-friendly and conventional vessels. First, the figure suggests that the two prices are almost perfectly positively correlated (the correlation coefficient is 99%). This is in line with the existing literature (e.g. Greenwood and Hanson, 2015) which suggests that vessel prices heavily depend on the prevailing TC rates which, in turn, are highly correlated.⁵ Second, it indicates that, when vessel prices increase (decrease), the price premium decreases (increases). As illustrated in Figure 4, the two facts combined imply that, when the price premium is low, freight market conditions are more prosperous, and the opposite.

⁵ The 1-year TC rates for the eco-friendly and conventional vessel types have a correlation coefficient of 99.9% (see Figure B1 in the Appendix).

This finding could be explained by the fact that the eco vessel provides more secured income compared to its counterpart. Namely, in normal/recessionary shipping markets, where the demand for vessels is relatively normal/low, a period charterer would prefer leasing first the eco-friendly vessel (as it is more fuel-efficient but also because of ESG principles that become increasingly important). Accordingly, the residual demand for vessels is not significant, which results in a larger TC premium and, thus, price premium during that period. Expansionary markets, in contrast, are equivalent to high demand for seaborne trade and tight supply of vessels. While eco vessels are still first employed realising very high TC rates, the increased residual demand pushes the TC rates of conventional ones high too – a relatively larger increase than the increase in the TC rates of the eco vessels. As a result, the TC and price premia decrease during expansionary periods.⁶

In line with the latter observation and to further examine the determinants of the price premium, the next section develops a threshold autoregressive model where the regimes depend on the prevailing freight market conditions.

III. Methodology and Empirical Results

The challenge of modelling eco vessels price premia lies in the intricate characteristics of their data generating process. Significant evidence in the literature suggests that second-hand vessel prices follow a nonlinear process. Specifically, Stopford (2008) points out that second-hand vessel prices may be state dependent. On the other hand, the stationarity (or the lack thereof) of the eco-vessels price premia has not been investigated so far. In the literature on second-hand vessel prices, most scholars rely solely on traditional unit root tests when examining this key statistical feature of the time series (Alizadeh and Nomikos, 2003; Haralambides et al, 2005). There is a strong consensus in the econometric literature that traditional unit roots tests may suffer from lack of power caused by the well-known finite sample size problem (Cavaliere and Xu, 2014). In our samples, we have circa 200 observations which span four years only, suggesting that the use of the Augmented Dickey Fuller or Philips-Perron tests may not be optimal.

Moreover, standard unit root tests are based on the assumptions of linearity and systematic adjustment of the data generating process and, thus, model as a permanent stochastic disturbance any departure from linearity. However, when the true data generating process is nonlinear, these tests have very low power and, thus, may fail to reject the null hypothesis (Carrasco, 2002). For these reasons, we employ tests that enable us to consider jointly unit roots and non-linearity. The results of these tests confirm that the data generating process is piecewise stationary (Appendix A discuss this in detail). As emphasised by Carrasco (2002), regime-switching models may capture piecewise non-linearities and structural changes. Thus, this kind of models offer a robust way in the identification of parameter instability in economic and financial time series. Moreover, regime-switching models allow for a better representation of the dynamics of the variable of interest (Clements et al., 2004; Carrasco et al., 2014).

⁶ From a wider shipping economics perspective, the sharp increase in the TC rates from February 2021 can be attributed to the gradual relaxation of the COVID-19 lockdown policies around the world, which significantly raised the demand for dry bulk cargoes as coal and iron ore that are transported by Capesize vessels.

Among the many alternative nonlinear models available in the literature (including Smooth Transition as well as Markov Switching models), in this paper, we account for the asymmetric relationship between the price premium and TC rates through the threshold autoregression (TAR) model of Hansen (1996) as it offers several advantages. First, switches in the regimes are governed by an observable threshold variable, thus, offering a direct interpretation of the findings. Second, the model captures non linearities by a piecewise linear approach which facilitates estimation via sequential least squares. Thanks to this characteristic, a TAR model is more effective when the time span of the analysis is not very long (Yau et al., 2015). The robustness of the model specification is reported in Appendix A1.

With this approach, we aim to test whether the impact of TC rates on vessel prices depends on the state of freight market conditions and to identify endogenously the threshold below or over which such effect differs. Regarding the proxy for freights market conditions, the TC rate for conventional vessels is used as opposed to the one for eco-friendly vessels, as the former should provide a more representative view of the entire sector. Since the aim is to capture the prevailing market conditions, we have tested the 6-month and 1-year TC rates (and not the 3- and 5-year contracts) and, through the sequential testing procedure proposed in Hansen (2000), we have chosen the most significant one. In the case of Capesizes, this is the 6-month TC rate and for Aframax, the 1-year TC rate.

The two-regime threshold autoregressive model is defined as follows:

$$y_t = \theta'_1 x_t I(Z_{t-k} < \lambda) + \theta'_2 x_t I(Z_{t-k} > \lambda) + u_t \quad (3)$$

for $t = 1, \dots, T$, where x_t is a vector of independent variables which can incorporate lagged values of the dependent one, an intercept, and a time trend; I is the indicator function; u_t is an i.i.d error term; and Z_{t-k} is the threshold variable, with k denoting the delay parameter and λ the threshold value. Here, each regime is characterised based on the overall freight market conditions, differentiating between normal/recessionary $I(Z_{t-k} < \lambda)$ and expansionary markets $I(Z_{t-k} > \lambda)$.

The slope parameters θ_i depends on the regime i . The number of regimes is unknown and estimated endogenously. The dependent variable, y_t , is the price premium analysed in Section II. In the model, all slope coefficients switch between the regimes, however, the model only allows for a subset of the coefficients to depend on the regime. We verify this following estimation of the models with the appropriate tests. The vector x_t includes the explanatory variables discussed in Section II. Given the relatively short period of our data, we select their lags with a general to specific exercise based on the Bayesian Information Criterion (BIC) (Fok et al., 2005).

While Equation (3) has non-linearity in the parameters, we can estimate it by sequential conditional least squares (Hansen, 2000). Under the further assumption of Normality of the idiosyncratic errors, least squares (LS) estimation is in fact equivalent to maximum likelihood estimation. From a specification point of view, it is necessary to check whether it is sensible to move from a linear to a non-linear specification model in (3). To this end, one needs to test the hypothesis that there are no asymmetries in the relationship between price and TC premia. This testing problem is non-standard due to the lack of identification of some of the parameters under the null hypothesis. Hansen (1996) demonstrates that the asymptotic distribution of the LR multiplier tests can be approximated through a bootstrap procedure.

Table 3 reports the estimation results, jointly with goodness of fit measures and significance tests, for the model specification where the 1-year TC premium is among the explanatory variables (in line with

the previous section, this is the reference case as 1-year TC rates are the most relevant ones from an asset pricing perspective). The p -values of the LR test statistics reported there support the evidence that the model is non-linear and allow us to reject linearity against threshold non-linearity. Furthermore, the p -value of the F-test confirms the overall statistical significance of the model irrespective of the sector and the regime and the adjusted R-squared figures, close to 90%, suggest a strong goodness of fit.

As mentioned above, our methodology offers the advantage of providing an endogenous estimate of the threshold. In line with Figure 2, the results suggest the presence of two regimes with the threshold being equal to USD 32,875 per day and to USD 32,000 per day for Capesize and Aframax vessels, respectively, and the delay parameter equal to 3 and 4 weeks, correspondingly. Regime 1 captures the eco price premium dynamics in normal/recessionary market conditions (i.e. when TC rates are below the relevant threshold) and Regime 2 refers to expansionary market conditions (i.e. when TC rates are equal to or above the respective threshold).⁷ The expansionary market is characterised by a higher volatility and a stronger and faster response to the TC rates than the normal/recessionary one.

To begin with, the results suggest that there is a strong persistence of the price premium, as quantified through the highly significant and large in magnitude coefficients of PP . This market stickiness suggests that shipowners should be able to resell the eco vessel in the future at a much higher price compared to the conventional one and, thus, justify the price premium previously paid also through higher capital gains compared to the case they were reselling the conventional one. A further finding is that the persistence of the past price premium is much stronger in normal/recessionary markets compared to expansionary ones with the slope coefficient being above 0.85 for both sectors in the former case and below 0.60 in the latter. This is in line with the asset pricing literature where prices appear to be stickier in relatively worse market conditions.

For the time-charter premia, which is the focal point of this estimation, the slope coefficient of TCP (time-charter contract premium), while significant in all cases, it is well below 1 – i.e. a one unit increase in the TC premium does not result in a one unit increase in the price premium – suggesting that TC rates cannot determine on their own the spread between eco-friendly and conventional vessel prices. This is in line with one of the main findings of this paper that price premia are on average well below the TC premia. However, it contrasts with the shipping asset pricing literature (e.g. Moutzouris and Nomikos, 2019) where the bulk of volatility of vessel prices can be attributed to movements of TC rates. Indeed, we see that other factors, as mainly past price premia and fleet supply, can explain the movements in price premia. Furthermore, we observe that the impact of TC premium is much bigger and faster in the expansionary regime, as reflected by the magnitude and lag of its coefficient, implying that a one unit increase in the TC premium will have a much larger effect on the price premium in expansionary markets rather than in normal/recessionary ones.

⁷ Due to the limited number of observations, a model specification with three regimes – that is recessionary, normal, and expansionary – would not be optimal. As such, the recessionary and expansionary market conditions are merged in a single state.

Table 3. Estimation results for the model with the 1-year TC rate.

	$j = \text{Capesize}$		$j = \text{Aframax}$	
	Threshold: $CTC_{t-3,j,0.5}$		Threshold: $CTC_{t-4,j,1}$	
	Regime 1 $CTC_{t-3,j,0.5} < 32,875$	Regime 2 $CTC_{t-3,j,0.5} \geq 32,875$	Regime 1 $CTC_{t-4,j,1} < 32,000$	Regime 2 $CTC_{t-4,j,1} \geq 32,000$
Obs. (n)	87	83	153	61
c	0.0003*** (0.0094)	0.0376*** (0.0062)	0.0041** (0.0180)	0.0514** (0.0220)
$PP_{t-1,j}$	0.9143*** (0.0000)	0.5707*** (0.0000)	0.8513*** (0.0000)	0.5598*** (0.0000)
$TCP_{t-1,j}$	-	0.5372*** (0.0015)	-	0.2502*** (0.0009)
$TCP_{t-2,j}$	0.0562*** (0.0042)	-	0.0569*** (0.0007)	-
$Supply_{t-4,j}$	1.8858* (0.0500)	2.1317* (0.0631)	-	-
$Supply_{t-8,j}$	-	-	1.2876** (0.0463)	2.7643** (0.0474)
$Fuel_{t-3}$	0.0019* (0.0530)	0.0476 (0.4800)	-	-
$Fuel_{t-4}$	-	-	0.0529*** (0.0026)	0.0011* (0.0911)
$LQ_{t-4,j}$	0.0031* (0.0140)	0.0046 (0.9713)	-	-
$LQ_{t-8,j}$	-	-	0.0018* (0.0215)	0.0021 (0.1874)
$\bar{R}^2$	0.8933	0.8872	0.9120	0.8841
$F - Stat$	1051.62*** (0.0000)		378.11*** (0.0000)	
$LR Test$	49.56*** (0.0030)		44.59*** (0.0000)	
Boostraps (n)	1,000		1,000	
Trimming	0.15		0.15	

This table reports the conditional LS estimates for the incorporated threshold models with two regimes, stating the estimated threshold as well as the number of observations that lie in the first and second regime, correspondingly. LR refers to the likelihood ratio test for the null hypothesis of no threshold, the p -value of which is estimated through bootstrapping, with n bootstrap replications, as proposed by Hansen (1996). Trimming refers to the percentage of total observations which are excluded from the sample to ensure a minimal percentage of observations lying in each regime. Figures in () are p -values. ***, **, * stating significance at the 1%, 5%, and 10% level, correspondingly.

The explanation for this could be related to the discussion about the past price premium. Namely, in expansionary markets where sentiment is high (Papapostolou et al., 2014), an increase in the TC premium can have a greater impact on the valuation of the eco-friendly vessel than the previous price premium but also than the fuel costs. In contrast, in normal/recessionary markets where investors are

less optimistic and, thus, more conservative and capital availability is reduced, past price premia and fuel costs can play a more significant role in the valuation for the eco-friendly vessel compared to the conventional one. In other words, if in expansionary markets, where TC rates for either vessel are already high, there is a larger increase in the TC rate for the eco vessel compared to the one for the conventional one, this signals to shipowners that investing in the eco vessel is indeed a reasonable decision. In contrast, in normal/recessionary markets, factors as fuel costs gain more importance in the valuation of the two vessels.

The slope coefficients for the fleet supply are significant, positive, and rather large in magnitude in all cases. Regarding the positive sign of the coefficient, Figure B2 (in Appendix B) demonstrates that, while vessels with modern eco engines constitute less than 50% of the total fleet, their fraction has rapidly increased, that is from less than 19% of the total fleet in early 2019 to more than 33% at the end of 2023. This increase becomes even more significant if one considers that these are fractions of the total existing fleet and not of the newly built vessels. Given that the average age of the Capesize and Aframax fleet in this period was above 8 and 10 years, respectively, modern eco vessels' contribution to the percentage increase in the fleet at a given point is (much) higher than the respective fractions in Figure B2.⁸ In other words, the relative supply of the eco-friendly fleet is increasing and the one for conventional vessels decreasing. This decreased appetite for conventional vessels and the increased supply of eco vessels might be driving the prices of the conventional vessels down and, thus, the price premium up. Furthermore, fleet supply has a larger effect on the price premium in expansionary markets as investor sentiment and capital availability are increased.

A further interesting finding of this research is related to the effect of fuel costs on the price premium depending on the prevailing market conditions and the shipping sector. Namely, in the Capesize sector, fuel costs are only significant in normal/recessionary markets; in the Aframax case, while fuel costs are significant in both regimes, the slope coefficient of *Fuel* (fuel costs) is much larger in normal/recessionary markets. This is because, in normal/recessionary markets, fuel prices amount to a much larger fraction of the vessel's income compared to expansionary ones. As such, a period charterer would prefer leasing first the eco-friendly vessel as it is more fuel-efficient (see Table 1) but also a ship owner operating the vessel in the spot market would realise a higher profit. Therefore, an increase in fuel costs has bigger effect on the price premium in normal/recessionary markets. However, the significance and magnitude of the fuel coefficient is much lower compared to the one for time-charter rates. A reason for this might be that fuel prices are either borne by the charterer in the case of a time-charter contract or by the shipowner in the case of a voyage charter. Moreover, the fact that fuels constitute both a cost and the commodity transported in the case of Aframax vessels can explain the stronger statistical significance of the respective coefficients compared to the Capesize sector where they are a cost only.

Finally, second-hand vessel transactions have a small impact on price premia as reflected in the small magnitude of the slope *LQ* (market liquidity) coefficients. A potential explanation for this is that (due to data unavailability) the variable only captures total vessel transactions and does not distinguish between eco and conventional vessels. Furthermore, one would expect that fleet development, that is changes in the aggregate supply of the fleet, plays a more significant role than second-hand vessel transactions which do not affect the supply-demand equilibrium of the industry and, thus, vessel

⁸ There are no data available for the number of newly built vessels with a modern eco engine.

prices. This is in line with both the literature and our findings where the slope coefficients of *Supply* are significantly larger than the ones of *LQ* in all cases.

Table 4. Test of equality of pairwise coefficients.

	<i>j</i> = Capesize	<i>j</i> = Aframax
	Wald Statistic	Wald Statistic
	Bootstrap <i>p</i> – values in ()	Bootstrap <i>p</i> – values in ()
$EP_{t-1,j}$	0.3 (0.629)	0.6 (0.651)
$ETC_{t-1,j}$	0.1 (0.808)	0.8 (0.721)
$Supply_{t-4,j}$	0.7 (0.567)	1.1 (0.483)
$Cost_{t-3}$	1.2 (0.401)	2.9 (0.521)
$LQ_{t-4,j}$	7.1 (0.068)	7.5 (0.054)
<i>c</i>	3.5 (0.218)	4.01 (0.341)

In addition to the parameter estimates, Table 4 reports the joint Wald tests for the pairwise equality of individual coefficients, and bootstrap *p*-values based on the null of no threshold. Looking at the point estimates and test results, it appears that the coefficients of the TC premium, fleet development growth, and fuel price are driving the threshold model, since we firmly reject the null hypothesis of no threshold, while the coefficients of the sales are either less important or displaying less variability across regimes.

To investigate the robustness of our findings, we re-estimate the model using the 5- year TC rates. Table 5 shows that the main results are similar to the ones discussed above. The only difference is that fuel costs in the Capesize case become significant at the 10% level also in expansionary markets (and larger in magnitude than in normal/recessionary markets). However, they are still much less significant than the one for the TC premium which is in line with the argument discussed in the 1-year TC case.

Table 5. Robustness of the estimation results to 5-year TC rates.

	$j = \text{Capesize}$		$j = \text{Aframax Vessels}$	
	Threshold: $CTC_{t-3,j,0.5}$		Threshold: $CTC_{t-4,j,1}$	
	Regime 1 $CTC_{t-3,j,0.5} < 29,530$	Regime 2 $CTC_{t-3,j,0.5} \geq 29,530$	Regime 1 $CTC_{t-4,j,1} < 28,750$	Regime 2 $CTC_{t-4,j,1} \geq 28,750$
Obs. (n)	81	89	144	70
c	0.0003*** (0.0090)	0.0571** (0.0217)	0.0591*** (0.0071)	0.0837** (0.0137)
EP	0.9144*** (0.000)	0.5707*** (0.000)	0.8280*** (0.000)	0.5758*** (0.000)
$TCP_{t-1,j}$	-	0.5172*** (0.008)	-	0.3543*** (0.0001)
$TCP_{t-2,j}$	0.0522*** (0.0020)	-	0.0166*** (0.0078)	-
$Supply_{t-4,j}$	1.7613** (0.0412)	2.0671* (0.0517)	-	-
$Supply_{t-8,j}$	-	-	1.1380* (0.0801)	3.4217*** (0.0087)
$Fuel_{t-3}$	0.0022* (0.0641)	0.0317* (0.0663)	-	-
$Fuel_{t-4}$	-	-	0.0357** (0.0141)	0.0033*** (0.0005)
$LQ_{t-4,j}$	0.0030* (0.0816)	0.0052* (0.0571)	-	-
$LQ_{t-8,j}$	-	-	0.0013** (0.0175)	0.0059 (0.4370)
$\bar{R}^2$	0.9041	0.9087	0.9089	0.8902
$F - Stat$	1318.01*** (0.000)		356.81*** (0.0000)	
$LR Test$	42.16*** (0.0002)		47.66*** (0.0001)	
Boostraps (n)	1,000		1,000	
Trimming	0.15		0.15	

This table reports the conditional LS estimates for the incorporated threshold models with two regimes, stating the estimated threshold as well as the number of observations that lie in the first and second regime, correspondingly. LR refers to the likelihood ratio test for the null hypothesis of no threshold, the p -value of which is estimated through bootstrapping, with n bootstrap replications, as proposed by Hansen (1996). Trimming refers to the percentage of total observations which are excluded from the sample to ensure a minimal percentage of observations lying in each regime. Figures in () are p -values. ***, **, * stating significance at the 1%, 5%, and 10% level, correspondingly.

IV. Further Discussion

From our analysis, the eco-vessel price premium is determined by the past price premium, TC rates, and fleet supply in expansionary markets, and by the past price premium, TC rates, fleet supply, fuel cost, and market liquidity in normal/recessionary markets. As such, the results reveal that neither the prevailing TC premia nor the cost of capital can explain on their own the observed price differential.

Instead, our TAR model suggests that past price premia and fleet growth have large in magnitude and statistically significant explanatory power. In this section, we first discuss these findings based on economic and financial foundations and then add the energy policy dimension, which eventually leads to a discussion about various uncertainties related to maritime decarbonisation. Finally, we discuss the limitations of the paper.

As illustrated in the previous sections, eco-friendly vessels trade at an average premium of close to 25% compared to their conventional counterparts. From an asset pricing perspective, this price premium could be explained by either higher freight rates or higher expected capital gains (i.e. resale prices) or lower cost of capital compared to the conventional vessel. Regarding the freight rates dimension, the TC premia are much lower, ranging from 9% to 15%, than the price premium which is 25%. Therefore, the long-term operating income generated by this investment can only partly justify this eco-friendly premium. Note that 1-, 3-, and, specifically, 5-year TC rates are considered as long-term operating income given the average demolition age for these vessel types, circa 24 years, and that the analysis is for vessels that are already 5-year-old. Furthermore, the strong persistence of the price premium also partly justifies the premium paid for the eco vessel through higher expected capital gains compared to the case they were reselling the conventional one. The latter argument is also in line with the fact that fleet development, and second-hand vessel sales in certain cases, have a strong positive relationship with the eco price premium (see also Appendix A2).

From the cost of capital perspective, despite recent developments in green/sustainable finance, discussed in previous sections, our findings suggest that the spread differential between green loans/sustainability-linked loans and standard loans is only 23 basis points. As such, the cost of capital does not seem to explain the observed eco premium. Nevertheless, the spread differential may become wider going forward. Currently, due to the inherently flexible nature of SLLs, these instruments tend to be more favoured by shipping companies. Although GLs have been used by shipping companies, their use is likely to increase alongside technological developments.

These findings may be explained by path dependency which refers to the theory that existing technology provides a path whereby firms innovate within this specific technology to improve its functional performance (Dosi, 1982; Thrane et al., 2010; Garud and Karnoe, 2013). In economic terms, path dependency indicates the difficulty of switching to a new technology path due to high switching costs, which can lead to the lock-in of established technologies. While a significant body of literature has studied path dependency in energy technologies (Lovio et al., 2011; Fouquet, 2016; Ćetković and Buzogány, 2020; de Freitas and Jehling, 2023), our research extends this theory to the shipping industry from a financial dimension. We observe that internal and systematic factors – as TC premia, price premia persistence, and fleet growth – rather than external factors – as fuel costs – are the main determinants of the prices of green technology in shipping. This may be explained by the fact that the current shipping market is a locked-in system where green technology faces high barriers to entry. Although shipping decarbonisation is on the agenda of many regulatory bodies, the pathway to achieving it remains unclear.

Furthermore, the current regulatory requirements may not be stringent enough to incentivise shipping investors who face high volatility and heavy capital demands. Given the much higher magnitude of the past price premia coefficients compared to the TC premia and fuel cost ones, as well as the marginal difference in interest rate spreads between GLs and SSLs and standard loans, shipping investors may benefit more from capital gains by buying and selling eco-vessels than from savings in

operational costs due to fuel efficiency or reduced financing costs with GLs or SSLs. Consequently, a small external shock is less effective than internal and systematic factors in the locked-in system that features large and long-term capital investment. In fact, the strong magnitude/persistence of past eco price premia suggest that the savings in fuel costs and financing costs from eco-vessels are still small compared to the potential capital gain in trading eco-vessels. The existence of path dependency in a locked-in system advocates for stronger policy intervention to guide a decarbonisation pathway (Stein, 2016; Goldstein et al., 2023), the same as in shipping. Policies such as carbon taxes and green subsidies will have to be robust and timely to counteract market forces stemming from internal and systematic factors.

However, the existing literature also demonstrates that energy technology adoption is affected not only by internal/systematic factors (such as innovation capacity within the firm or the industry) but also by external factors such as fuel prices, carbon taxes, and green funding and subsidies (Popp, 2002; Aghion et al., 2016; Howell, 2017; Stucki et al., 2018; Çınar and Yilmazer, 2021). In other words, our results emphasise the need for policymakers to implement market-based measures and/or financial tools to encourage eco-vessel investment by either increasing the TC premium paid for eco vessels or/and increasing the interest rate (i.e. cost of capital) spread between eco and conventional vessel investments. Our findings in shipping finance diverge from the literature. We find that internal and systematic factors have much higher impact than external factors on clean energy technology adoption. This discrepancy may be explained by the high volatility of the shipping market, where market failures (such as herd behaviour) obstruct the influence of external factors. We propose that in volatile markets, internal and systematic factors play a more crucial role in determining green technology product prices. Our findings may also apply to other volatile markets, such as the technology equity market (Mulligan, 2004).

In a highly volatile industry as shipping, capital market failures may amplify the effects of internal and systematic factors, resulting in distorted prices of green technology. Previous research emphasises that negative pollution externalities and positive knowledge spillover result in unfair pricing of green technology (Jaffe et al., 2005). Our research contributes to the literature by pointing out two additional concepts in capital market failures that may distort the real value of green technology, that is herd behaviour (or momentum investment) and risk aversion. Herd behaviour refers to imitative patterns that build up and affect the entire system and has been studied in the finance context for a few decades – defined as investors making decisions based on others' actions instead of adequate information (Avery and Zemsky, 1998; Bikhchandani and Sharma, 2000). This can cause momentum investment, where investors buy or sell assets based on past returns, resulting in exacerbated price movements and increased volatility (Grinblatt et al., 1995; Nofsinger and Sias, 1999). Herd behaviour and momentum investment contradict the efficient market hypothesis that market prices incorporate all available information (Fama, 1970). Herd behaviour also influences shipping asset pricing (Papapostolou et al., 2014, 2017; Alizadeh et al., 2017). In line with this argument, the documented persistence of price premia might be attributed to herd behaviour reactions to past prices and fleet supply.

While herd behaviour can affect vessel pricing, risk aversion limits private capital investment in eco-technologies due to financial, regulatory, and technological risks (Chronopoulos and Siddiqui, 2015; Sendstad and Chronopoulos, 2021; Yu et al., 2021). Although scholars have found that both risk-averse and risk-loving investors participate in the shipping market (e.g. Alizadeh et al., 2017), little

information is provided on the risk appetite for eco-vessels. As such, this paper aims to emphasise the importance of clarity and certainty about whether and how new potential decarbonisation regulations will be actually implemented in shipping. Namely, one needs to consider the increasingly strict regulations in the form of the revised and more ambitious 2023 IMO GHG Strategy as well as any associated policies such as the potential adoption of market-based-measures (e.g., carbon prices/taxes) in the coming years and the inclusion of shipping in the EU ETS from January 2024. The market-based measures and the certainty regarding the implementation of the IMO GHG strategy are expected to provide a strong competitive advantage to eco vessels over their conventional counterparts. This advantage is reflected in the significant spreads between eco and non-eco freight rates, and consequently, vessel prices. Thus, in line with the documented persistence of the price premium, investing in the (much) more expensive eco vessel, could be perceived as a rather medium- to long-term strategy.

The analysis so far has focused on the price differential between second-hand eco and conventional vessels. Despite the challenges mentioned above, however, this investment decision is associated with much less technological uncertainty compared to the case of new building vessels. The latter can have an economic life of 25 years or more and require in-depth consideration of factors such as future availability and price of alternative fuels (such as LNG, methanol, hydrogen, ammonia, biofuels, synthetic/e-fuels, nuclear energy, etc.), the required technology and specifications for a vessel to burn those, how the current and forthcoming regulations (which can vary among jurisdictions) can affect the industry but also safety concerns related to alternative fuels as ammonia.

Therefore, shipowners not only face the dilemma of whether to invest in a cheaper but (much) more polluting conventional vessel or in a more expensive but eco-friendly one but also whether it is rational to postpone their investment decision for when there is more clarity regarding technology and the implementation of potential new decarbonisation regulations. While, traditionally, the investment decision of shipowners was associated with the current and expected freight market conditions, recent evidence suggests that the introduction of the decarbonisation uncertainty has, on the one hand, weakened the effect of freight rates on new building investment and, on the other hand, has negatively affected shipping investment as a whole. Namely, while from January 2005 to March 2018 there was a 58% correlation between investment in newbuilding vessels and freight market conditions, this has decreased to 21% from April 2018 and the adoption of the Initial IMO Strategy on the reduction of GHG emissions from ships. While for the period 2020- 21 the COVID-19 pandemic may also have contributed to the lower correlation between the decision to invest and freight market conditions and expectations, these trends have persisted in the following years. Also, the average monthly investment in the period from April 2018 to September 2023 has decreased by 29% compared to the period from January 2005 to March 2018 (Figure B3). Regarding the two sectors under consideration in this paper, as of September 2023, the existing fleet consisted of 7,535 tankers ($\geq 10,000$ DWT) with an average age of circa 13 years and 13,609 dry bulk vessels with an average age of circa 12 years. At the same time, the orderbooks were 6% and 8% of the fleet, respectively (Clarksons', SIN). This underinvestment in newbuilding vessels can have important adverse effects on the mid- to long-term supply of the fleet and, in turn, of the efficient facilitation of world seaborne trade.

As such, to reach the IMO environmental targets without threatening the well-functioning of the shipping industry and world trade, there is an increasing need for consensus among the different regulatory authorities and the various shipping and maritime stakeholders. Reaching a consensus will

reduce perceived risk and uncertainty in investing in eco-vessels, thereby encouraging a timely and effective market response to shipping decarbonisation. Regulators need to take actions promptly to set a clear decarbonisation strategy with respect to e.g. market-based measures as the implementation of carbon taxes and the corresponding tax levels and timelines.

There are limitations to this paper. From a technological point of view, it is expected that the eco-vessel price premium is determined by the cost of green technology in shipping. Due to lack of relevant available data though and as the focus of the paper are the economic and financial determinants of the eco price premium, we have not conducted an empirical analysis on how technological or regulatory factors may influence eco-vessel investment. Also, due to unavailability of relevant data, we cannot provide any concrete advice on green finance policies, such as the specific amount of subsidy needed to incentivise eco-vessel investment.

V. Conclusions

This research was motivated by the recent regulatory developments around shipping decarbonisation (i.e. IMO GHG Strategy and EU ETS) and numerous related discussions and events with various stakeholders, including ship owners/operators, financiers, ship brokers, market analysts, charterers, and regulators. The main outcomes of those discussions are aligned with the findings presented in this article.

This paper contributes to the literature on green technology by analysing shipping sustainability from the economic and financial dimensions. To begin with, we find that, while eco-friendly vessels trade at a roughly 25% premium compared to their conventional counterparts, the cash inflows generated by the former are only 9%-15% higher than the ones by the latter. Furthermore, the cost of capital of eco vessels appears to be only marginally lower. Moreover, we find that the price premium is lower in prosperous market conditions compared to normal/recessionary markets and we relate this result to the supply and demand shipping mechanism.

We further investigate the determinants of the price premium using a threshold autoregressive model that allows us to test and analyse the non-linear relationship between eco price premia and various shipping economic and financial variables, depending on freight market conditions. The empirical results suggest that time-charter premia, price premia persistence (which reflects market stickiness) and growth in the fleet supply have a significant impact on the differential between eco-friendly and conventional vessel prices and, to a lesser extent, factors market liquidity and fuel costs. Furthermore, we find that the impact of time charter rates is more pronounced during expansionary phases of freight markets, which are also characterised by higher volatility and less persistence of price premia.

Finally, additional analysis suggests that there is no clear evidence of significantly lower cost of capital for green shipping investments. This leads to a discussion about the theoretical framework in shipping decarbonisation and its policy implications. The results may be explained by two prevalent issues in green technology diffusion: path dependency and capital market failures. Path dependency exacerbates the effects of internal and systematic factors in a locked-in system. Capital market failures, including herd behaviour and risk aversion, distort the fair pricing of green technology products. The paper also suggests that the introduction of the decarbonisation uncertainty has, on the one hand, weakened the effect of freight rates on new building investment and, on the other hand, has negatively affected shipping investment as a whole. This raises concerns not only about the

decarbonisation progress of the shipping industry, but also about its well-functioning and the facilitation of seaborne trade in the coming years. Policy makers and regulators need to provide more clarity about future incoming regulations, such as market-based measures, and/or introduce further green finance tools, in a timely manner.

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Appendix A: Stationarity and Robustness

Appendix A1: Stationarity Tests

Table A1. Panel A: Threshold Wald Tests.

	Capesize			Aframax		
	WT	1% C.V.	-value	WT	1% C.V.	-value
1	20.4	20.0	0.008	18.24	21.0	0.006
2	27.0	20.1	0.001	23.10	20.1	0.001
3	22.7	20.3	0.004	25.37	24.8	0.002
4	27.0	20.1	0.001	26.09	22.3	0.002
5	38.1	20.5	0.000	35.41	22.3	0.000
6	40.0	20.2	0.000	35.61	12.5	0.001
7	34.0	19.9	0.000	34.04	19.1	0.000
8	46.9	20.7	0.000	38.59	18.7	0.001
9	61.1	20.4	0.000	56.31	21.1	0.000
10	56.8	20.8	0.000	51.38	19.2	0.000
11	52.8	20.3	0.000	55.58	19.6	0.000
12	62.6	20.5	0.000	75.66	12.5	0.000

Notes: denotes the delay parameters; WT stands for the value of the Wald test; CV the 1% bootstrap critical value; and -value the bootstrap -values calculated from 10,000 replications.

Table A1. Panel B.

Sup LR Unit Root tests for Capesize Vessels.

	Capesize		Aframax		Panamax	
	Asym.	Boot.	Asym.	Boot.	Asym.	Boot.
1	0.001	0.012	0.004	0.104	0.031	0.038
2	0.008	0.014	0.003	0.362	0.037	0.019
3	0.017	0.004	0.009	0.037	0.046	0.012
4	0.011	0.042	0.008	0.026	0.047	0.097
5	0.014	0.034	0.029	0.013	0.025	0.034
6	0.009	0.012	0.000	0.033	0.001	0.041
7	0.001	0.008	0.003	0.046	0.093	0.038
8	0.005	0.008	0.016	0.025	0.031	0.008
9	0.042	0.009	0.036	0.015	0.016	0.035
10	0.006	0.008	0.005	0.027	0.031	0.048
11	0.016	0.008	0.016	0.040	0.003	0.040
12	0.105	0.002	0.001	0.057	0.009	0.003

Sup LR Unit Root tests for Aframax Vessels.

	Asym.	Boot.	Asym.	Boot.	Asym.	Boot.
1	0.002	0.008	0.003	0.099	0.019	0.026
2	0.003	0.009	0.004	0.102	0.026	0.011
3	0.006	0.007	0.008	0.044	0.029	0.008
4	0.009	0.011	0.007	0.019	0.031	0.045
5	0.011	0.014	0.002	0.009	0.025	0.017
6	0.012	0.009	0.001	0.011	0.001	0.026
7	0.001	0.005	0.006	0.007	0.093	0.019
8	0.001	0.009	0.011	0.013	0.031	0.003
9	0.013	0.011	0.007	0.005	0.016	0.029
10	0.014	0.006	0.009	0.013	0.009	0.028
11	0.015	0.008	0.011	0.027	0.003	0.051
12	0.009	0.001	0.000	0.034	0.006	0.015

Note: The table reports the threshold statistics of unit root tests based on the sup LR test, namely the R , $t1$, and $t2$, for each of the delay parameters, m , from 1 to 12, as well as the asymptotic and the bootstrap p -values.

As discussed in the main empirical section, establishing the stationarity or lack thereof is a key preliminary step of model identification. Due to the short time span of the data and the strong nonlinearity of the eco price premium data generating process, we employ tests that enable us to consider jointly unit roots and non-linearity. Specifically, we implement the test proposed by Carner and Hansen (2001) which allows to test for the presence of a unit root and of non-linearity using a Wald test for threshold effects and t tests and the sup LR and for unit roots. We focus on the sup Likelihood Ratio (LR) test for stationarity since it is more reliable than the Lagrange Multiplier (LM) and Wald tests in smaller samples (Bec at al., 2004). The respective results are reported in Table A1 below.

Carner and Hansen (2001) have obtained and tabulated the limit distributions for the tests and their critical values, respectively. While the unit root tests seem to follow an asymptotic bound distribution, we rely on bootstrap procedures to approach the sampling distribution. Table 3, Panel A reports the Wald test, the 1% bootstrap critical value, and the bootstrap p -value for delay parameters m from 1 to 12 and threshold $\Delta y_t = y_t - y_{t-1}$. The tests reject the null hypothesis of no threshold for any choice of m , suggesting that a threshold regression specification is strongly supported by the data. Table 3, Panel B reports the threshold unit root test statistics based on the sup LR test, namely the R , $t1$, and $t2$, for each delay parameter m , from 1 to 12, and the asymptotic and bootstrap p -values. The asymptotic p -value bounds are estimated incorporating the p -value functions reported by Carner and Hansen (2001). The R test statistics appear to be significant at the 1% level; hence, the one-sided sup LR test of unit root versus the two-regime stationary nonlinear model can be rejected. Regarding the individual t -ratios, we observe that the p -values strongly suggest that we can reject the null hypothesis of unit root in each regime suggesting that the estimated model is piecewise stationary.

Appendix A2: Robustness

A potential source of concern in our empirical analysis is the short period of the available data for eco price premia, which ranges from 2019 to 2023. To address this concern, we report below results from a multiple linear regression model where the regime switch in February 2021 (in line with Footnote 8 and with the results from the TAR model) is captured through a dummy variable. The model is fully linear by construction and its use is intended only as a robustness check for the reader. Table A2 reports estimation results and tests. The estimated coefficients capture the impact of the explanatory variables before the structural break in February 2021 and the interaction dummies coefficients capture their change after the break. To facilitate comparison, we construct the slope dummies to identify changes from regime 1 to 2. Namely, the first column reports the estimates of the linear coefficient and the second one the estimated coefficients of the interaction term, thus, the variation in the estimated coefficient across the two regimes identified by the dummy variable. The estimation results and statistical tests support the findings from the TAR model as they confirm the significance of the selected regressors in explaining the dynamics of the eco price premium over time. The high significance of the interaction dummy estimated coefficients suggests that, indeed, after the regime switch, the coefficient magnitudes are subject to significant changes of the same size and sign as the ones reported in Section III.

Table A2. Estimation results for the model with the 1-year TC rate.

	$j = \text{Capesize}$		$j = \text{Aframax}$	
	Dummy: <i>Feb</i> 2021		Dummy: <i>Feb</i> 2021	
Obs. (n)	193		214	
c	0.0003*** (0.0076)	0.0322*** (0.0000)	0.0046* (0.0512)	0.0471*** (0.0003)
$PP_{t-1,j}$	0.9143*** (0.0000)	-0.2889*** (0.0000)	0.8489*** (0.0006)	-0.2915*** (0.0000)
$TCP_{t-1,j}$	0.0781* (0.0597)	0.3181*** (0.0005)	0.0421* (0.0712)-	0.2074*** (0.0003)
$Supply_{t-4,j}$	1.7613* (0.0513)	0.3662*** (0.0003)	-	-
$Supply_{t-8,j}$	-	-	1.2716* (0.0512)	1.3826*** (0.0009)
$Fuel_{t-3}$	0.0023* (0.0603)	0.0451*** (0.0012)	-	-
$Fuel_{t-4}$	-	-	0.0522*** (0.0059)	-0.0381** (0.0432)
$LQ_{t-4,j}$	0.0031* (0.0561)	0.0349*** (0.0009)	-	-
$LQ_{t-8,j}$	-	-	0.0016* (0.0715)	0.0005** (0.0794)
$\bar{R}^2$	0.8012		0.8361	
$F - Stat$	947.05*** (0.0000)		303.06*** (0.0000)	

Table A3. Estimation results for the model without the past price premium.

	$j = \text{Capesize}$		$j = \text{Aframax}$	
	Threshold: $CTC_{t-3,j,0.5}$		Threshold: $CTC_{t-4,j,1}$	
	Regime 1 $CTC_{t-3,j,0.5} < 32,875$	Regime 2 $CTC_{t-3,j,0.5} \geq 32,875$	Regime 1 $CTC_{t-4,j,1} < 32,000$	Regime 2 $CTC_{t-4,j,1} \geq 32,000$
Obs. (n)	87	83	153	61
c	0.0003*** (0.0094)	0.0376*** (0.0062)	0.0041** (0.0180)	0.0514** (0.0220)
$LQ_{t-1,j}$	0.4521*** (0.0000)	0.4121*** (0.0000)	0.6215*** (0.0000)	0.6671*** (0.0000)
$LQ_{t-2,j}$	0.1712*** (0.0005)	0.1981*** (0.0007)	0.1761*** (0.0001)	0.1332*** (0.0003)
$LQ_{t-3,j}$	0.0871*** (0.0005)	0.0739*** (0.0000)	0.0692*** (0.0000)	0.0579*** (0.0000)
$LQ_{t-4,j}$	0.0031* (0.0140)	0.0046 (0.9713)	-	-
$LQ_{t-8,j}$	-	-	0.0018* (0.0215)	0.0021 (0.1874)
$TCP_{t-1,j}$	-	0.5372*** (0.0015)	-	0.2502*** (0.0009)
$TCP_{t-2,j}$	0.0562*** (0.0042)	-	0.0569*** (0.0007)	-
$Supply_{t-4,j}$	1.8858* (0.0500)	2.1317* (0.0631)	-	-
$Supply_{t-8,j}$	-	-	1.2876** (0.0463)	2.7643** (0.0474)
$Fuel_{t-3}$	0.0019* (0.0530)	0.0476 (0.4800)	-	-
$Fuel_{t-4}$	-	-	0.0529*** (0.0026)	0.0011* (0.0911)
$\bar{R}^2$	0.6983	0.6772	0.7013	0.6861
$F - Stat$	562.17*** (0.0000)		365.24*** (0.0000)	
$LR Test$	41.32*** (0.0030)		40.33*** (0.0000)	
Boostraps (n)	1,000		1,000	
Trimming	0.15		0.15	

This table reports the conditional LS estimates for the incorporated threshold models with two regimes, stating the estimated threshold as well as the number of observations that lie in the first and second regime, correspondingly. LR refers to the likelihood ratio test for the null hypothesis of no threshold, the p -value of which is estimated through bootstrapping, with n bootstrap replications, as proposed by Hansen (1996).

Trimming refers to the percentage of total observations which are excluded from the sample to ensure a minimal percentage of observations lying in each regime. Figures in () are p -values. ***, **, * stating significance at the 1%, 5%, and 10% level, correspondingly.

Furthermore, the estimated models in Tables 3, 5, and A1 identify a strong positive relationship between the past price premium and the current price premium. This finding suggests that there is high persistence or, in other words, stickiness of the price premium in the sale-and-purchase second-hand market for ships. To investigate this interpretation further, we re-estimate the basic model replacing the past price premium term with lagged values of the market liquidity variable (i.e. second-hand vessel sales). The results reported below are consistent with our main findings and also confirm that, even without the past price premium included in the model, TC, fleet supply, market liquidity, and fuel cost can explain the observed price premium (with a very high R-squared of around 70%).

Appendix B: Additional Figures

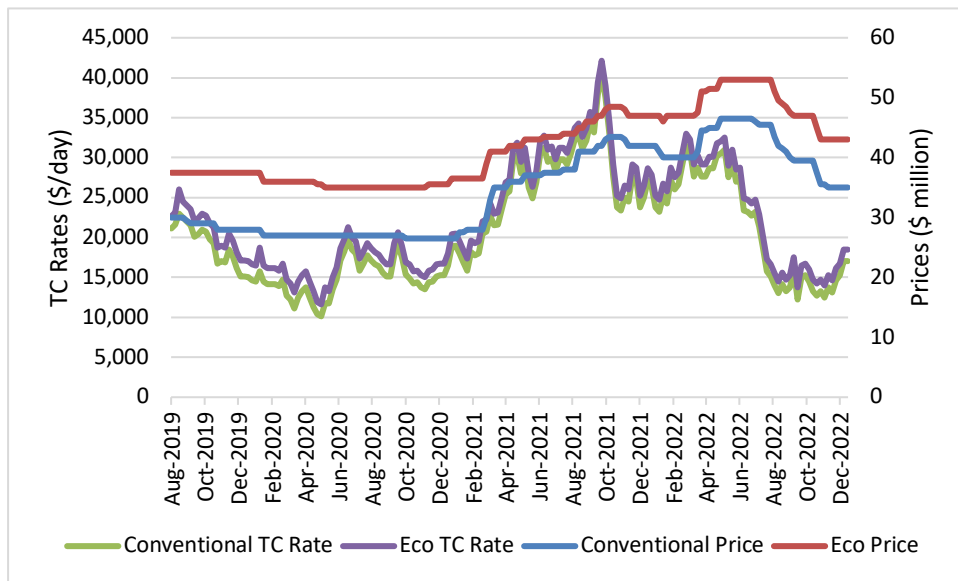


Figure B1: Vessel prices and TC rates for the conventional and eco-friendly vessels.
Source: Data are from Clarksons' SIN.

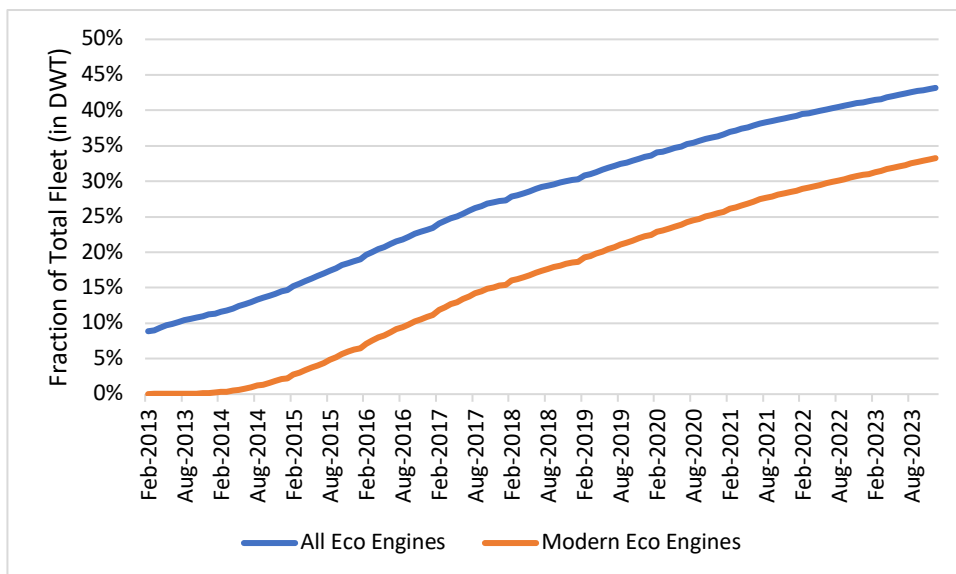


Figure B2: Vessels with eco and modern eco engines as fraction of the total fleet.
Source: Authors' calculations. Data are from Clarksons' SIN.

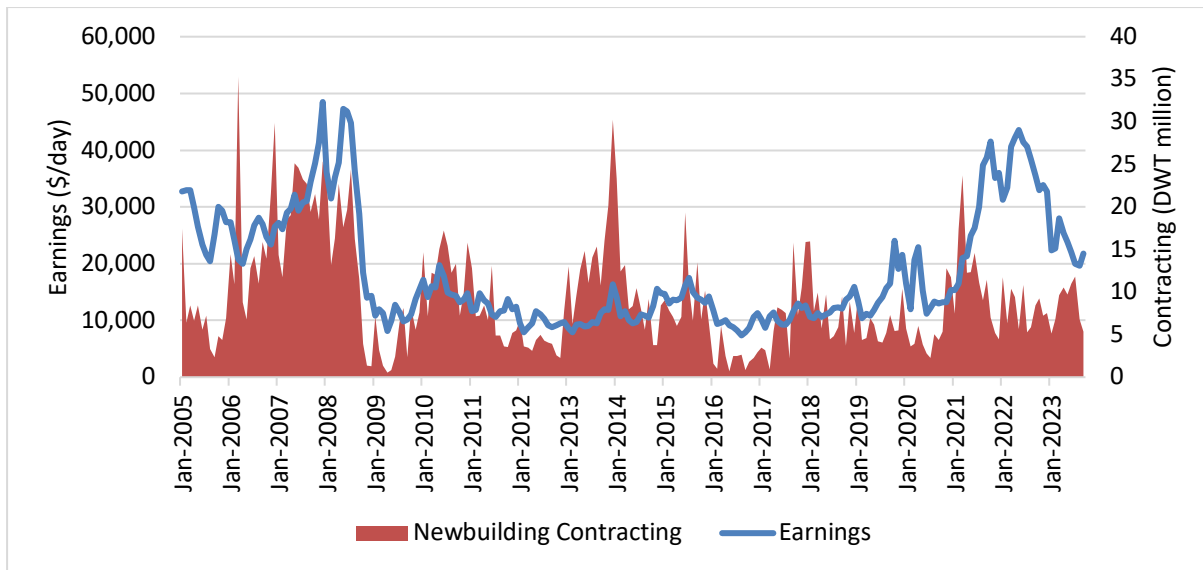


Figure B3. Average vessel earnings and investment in newbuilding vessels.

Notes: Earnings refer to the Clarksea Index which tracks average vessel earnings across the major shipping sectors, including tankers, bulkers, containerships and gas carriers, weighted by the number of ships in each segment. Newbuilding contracting refers to the new orders of newbuilding vessels for all vessels of at least 20,000 deadweight tonnage capacity. Source: Clarksons' SIN.