Impact of fuel prices on energy efficiency of maritime ships

CE Delft

Committed to the Environment

Impact of fuel prices on energy efficiency of maritime ships

This report was prepared by:
Arno Schroten, Dagmar Nelissen, Ward van Santen, Peter Scholten and Joukje de Vries

Delft, CE Delft, October 2024

Publication code: 24.230477.108

Client: Transport & Environment

Publications of CE Delft are available from www.cedelft.eu

Further information on this study can be obtained from the contact person Arno Schroten (CE Delft)

Content

Summary

Over the last decade, several policies have been implemented by the International Maritime Organisation (IMO) and the European Commission (EC) to affect the environmental performance of maritime shipping. Many of these policies result in higher fuel costs for shipping, either direct (e.g. in case of EU ETS) or indirect (e.g. in case of FuelEU Maritime[1]). In this study, we have investigated whether and to what extent increases in fuel prices influence shipping companies to invest in energy efficiency technologies or to improve their operational energy efficiency. For that purpose, we have econometrically studied the impact of historic variations in fuel prices on both technical and operational energy efficiency of maritime ships in the global fleet.

Impact of fuel prices on technical energy efficiency of new-build ships

Based on the econometric analyses carried out, we conclude that there is significant evidence for a positive relationship between fuel price levels and the technical energy efficiency of new-build ships. In other words, our analyses show that high fuel prices incentivise ship owners to build more energy efficient vessels. As an illustration: one of our models shows that, on average and all other factors kept equal, a 1% increase in fuel prices leads to a 0.26% increase in technical energy efficiency (EIV) of new-build vessels six years later (significance level: 99%; R^2: 0.63).

The relationship between fuel prices and technical energy efficiency of new-build ships turns out to be different for different ship types: the efficiency of tankers is less sensitive to fuel price changes than container ships, while the price effect is close to zero for bulk carriers. Furthermore, it seems that ship owners (from all types of ships) consider long-term (historic) trends (up to 20 years) in fuel prices when deciding on the energy efficiency of new-build ships. This implies that policies targeting fuel prices may take considerable time to effectively influence the technical efficiency of (newly built) maritime ships.

The relationship between fuel prices and technical energy efficiency of new-build ships has been studied based on data for the period 1990–2024. Particularly in the first 25 years of this period, the number of policies targeting the energy efficiency of maritime vessels was very limited. Therefore, it may be questioned to what extent the relationship between fuel prices and technical energy efficiency estimated for this period will be representative for the current situation, where several policies have been (or will be) implemented to improve the energy efficiency of maritime shipping. We found evidence that the relationship between fuel prices and the technical energy efficiency of new-build ships is less strong after 2015. This suggests that the relationship between fuel and EIV is in fact affected by the implementation of other policies, like the EEDI or the EU MRV.

To our knowledge, this study is the first to provide statistical evidence for the existence (and magnitude) of the relationship between fuel prices and technical energy efficiency of new-build maritime ships. In this way it complements the current literature on this topic, which only provides theoretical or fragmented evidence for the existence of this relationship.

[1] FuelEU Maritime regulates the yearly average Well-to-Wake Greenhouse Gas intensity of energy used on board of ships trading in the EU. This policy incentivises the use of low-carbon fuels, and as the costs (per MJ) of these fuels are higher than for conventional fuels, this results indirect in higher fuel costs.

Impact of fuel prices on operational energy efficiency of maritime ships

One of the options to improve the operational energy efficiency of maritime ships is by lowering their average sailing speed. Our econometric analyses do, however, not provide significant evidence for this relationship. On the contrary, we found a small positive relationship between fuel prices and sailing speed, which would imply that higher fuel prices lead to higher sailing speeds. However, the fit of the econometric models estimated was very poor. Most likely, relevant variables explaining variations in sailing speed (e.g. weather conditions, contract details, etc.) were missing from the analysis. Due to a lack of data, we were not able to include these variables in our analyses. From the literature, it is, however, clear that these variables are important explanatory factors for average vessel speeds.

Potential policy impacts

The results of the econometric analyses as described above, do not show statistical evidence that policies resulting in higher fuel prices may lead to higher energy efficiency in the short term.[2] On the other hand, we did find significant evidence that policies may affect the technical energy efficiency of new-build maritime ships in the longer run. These results may be used to investigate the impact of specific policies leading to fuel price variations on the technical efficiency of maritime vessels.

To illustrate the way the results of this study can be used, we have estimated the impact of the inclusion of maritime shipping in EU ETS and the introduction of FuelEU Maritime on the technical energy efficiency of new-build maritime vessels. We found that the increases in fuel costs due to these policies leads to an improvement of the technical energy efficiency of ships coming to the market in the period 2031-2035 by roughly 1%. Due to the long lifetime of maritime vessels, the impact on the average technical energy efficiency of the fleet is more limited, about 0.03% for the period 2030-2035. Although this estimation depends on a large amount of assumptions and should be interpreted carefully, it provides a first order estimation of the order of magnitude of this effect.

Approach followed

To assess the relationship between fuel prices and technical efficiency of new-build vessels, we used an Ordinary Least Squares (OLS) regression based on yearly data between 1990 and 2024. Although the model provides highly significant results and a good model fit, applying these results to estimate potential policy effects is not straightforward as they are based on historic data, which has limited value for future projections. This is illustrated by the assessment of potential policy impacts described above.

We applied a panel data analysis to assess the relationship between average vessel speed and fuel prices. For this analysis we made use of data on monthly basis for various types of ships between 2012 and 2024. The relationship between fuel prices and average vessel speed is considered across all ship types, and for container ships and tankers/bulk carriers separately. Unfortunately, the model gives a poor fit, as much of the variation in the real-world data is filtered out due to the nature of the averaged-out data. As such, we recommend that this model is revisited if or when more granular data (on individual ship-level, at a higher frequency) is available, in order to account for more variability in terms of ship behaviour and quickly-changing conditions, such as the daily weather conditions and/or contractual obligations.

[2] Based on our study, we cannot conclude that this relationship is not existing, but we didn't find any proof for it.

1 Introduction

1.1 Background

Over the last decade, several policies have been implemented to affect the environmental performance of maritime shipping. Over the last decade, the International Maritime Organisation (IMO) has introduced several standards to improve the energy efficiency of newly build and existing ships as well as the operational energy efficiency of ships (see Textbox 1). In 2017 the EU introduced the mandatory Monitoring, Reporting and Verification (MRV) of CO_2 emissions of all ships above 5,000 gross tonnage (GT) on EU related voyages (EC, 2020). By implementing FuelEU Maritime, the EU regulates for ships trading in the EU that the yearly average Well-to-Wake GHG intensity of energy used on board (measured as gCO_2-eq/MJ) needs to be below a required level. This regulation, which will come into force in 2025, intends to increase the share of renewable and low-carbon fuels in the fuel mix of international maritime transport in the EU. Furthermore, the EU Emission Trading System (EU ETS) has been extended to maritime transport emissions since 1 January 2024.
In addition to these climate policies, policies targeting air pollutant emissions have been implemented as well. These include, for example, the implementation of Emission Control Areas (ECAs) and global sulphur caps for marine fuels.

Textbox 1 - Current IMO policies to reduce carbon emissions of maritime shipping

Over the last decade, the IMO has introduced several policies to reduce the CO_2 emissions of maritime shipping. These so-called short-term measures include:

- **Energy Efficiency Design Index (EEDI)**, which prescribes a minimum technical energy efficiency of new-builds.
- **Energy Efficiency Existing Ship Index (EEXI)**, which is an index measuring the technical efficiency of all existing vessels. It came into force on 1 January 2023. An individual ship's attained EEXI indicates its energy efficiency compared to a baseline. The attained EEXI will be compared to a required Energy Efficiency Existing Ship Index based on an applicable reduction factor expressed as a percentage relative to the Energy Efficiency Design Index (EEDI) baseline.
- **Ship Energy Efficiency Management Plan (SEEMP)** is a plan to improve the (operational) energy efficiency of individual ships. All ships of 400 gross tonnage (GT) and above engaged in international voyages must develop and keep on board a SEEMP.
- **Carbon Intensity Indicator (CII)** is an indicator of the operational carbon intensity of individual ships expressed in CO_2/cargo-capacity-miles. The CII determines the annual reduction factor needed to ensure continuous improvement of a ship's operational carbon intensity within a specific rating level (A up to E). The actual annual operational CII achieved must be documented in the SEEMP and verified against the required annual operational CII.

Many of the policies mentioned before, result in higher fuel cost of shipping, either directly (in case of EU ETS) or indirectly (in case of FuelEU Maritime, ECAs and sulphur caps for marine fuels). For example, FuelEU Maritime requires ship owners to increase their use of renewable or low-carbon fuels. As the costs of these fuels exceed the costs of fossil fuels, it will result in higher fuel costs for ship owners.

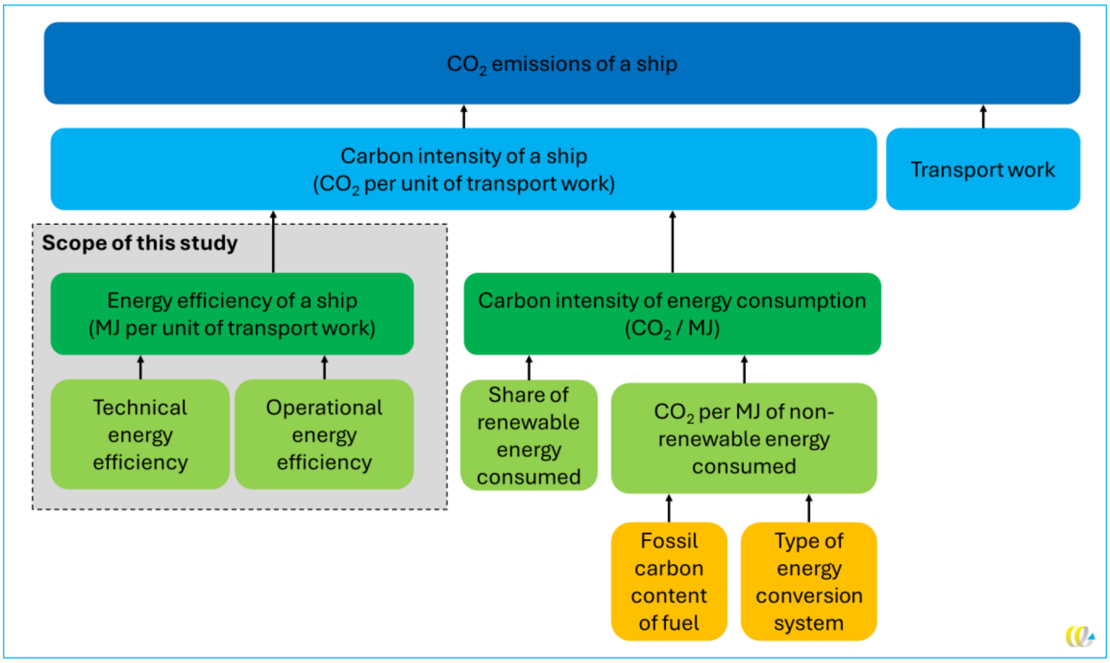
T&E is interested in getting a better understanding of how these increases in fuel costs will influence shipping companies to invest in energy-efficiency technologies or to improve their operational energy efficiency (e.g. by lowering the average speed of their ships). For that reason, they requested CE Delft to empirically assess the relationship between historic fuel prices and the energy efficiency of maritime ships. A better understanding of this relationship will help in analysing the energy-efficiency improvements expected as result of the main EU shipping climate laws (i.e. EU ETS, FuelEU Maritime).

1.2 Objective and scope of the study

The overall objective of the study is to assess whether and to what extent fuel prices affect the energy efficiency of maritime ships. The results of this analysis can be used to (roughly) estimate the energy-efficiency improvements that may be expected from the inclusion of maritime shipping in EU ETS and the implementation of FuelEU Maritime.

The energy efficiency of ships (defined in MJ per unit of transport work, e.g. tonne-kilometres) depends on both the technical and operational energy efficiency of ships (see Figure 1). The **technical energy efficiency** depends on the design of the ship, and depends on factors like the engine configuration, hull design, auxiliary engines on board, etc. **Operational energy efficiency**, on the other hand, refers to the impact the use of the ship has on the actual energy consumption. It depends on the actual speed of the ship, the routes taken by the ship (e.g. different weather and wave conditions significantly affect the energy consumed), the load factor, level of maintenance and cleaning of hull and propeller, etc. In this study, we both consider operational and technical energy efficiency of maritime ships.

Figure 1 - Determinants of CO_2 emissions, carbon intensity and energy efficiency of maritime transport



As indicated by Figure 1, this study focuses on the energy efficiency of maritime ships. Energy efficiency is, however, closely related to carbon efficiency. The main difference between both concepts is that carbon efficiency is (theoretically) affected by the carbon content of the fuels applied, while energy efficiency is not. However, as the use of renewable energy in maritime transport is still very limited, the carbon content of fuels used by maritime ships is almost constant. As a consequence, energy and carbon efficiency are directly linked and therefore carbon efficiency is often used as an indicator for energy efficiency. For example, the Energy Efficiency Operational Indicator (EEOI), which has been developed by the IMO in order to allow shipowners to measure the fuel efficiency of a ship in operation, uses CO_2 emissions per ton-miles instead of MJ per ton-miles as metric. Therefore, carbon-efficiency indicators of maritime ships are an option to be used as a proxy for energy efficiency of ships for the purpose of this study.

As this study focuses on energy efficiency of maritime ships, the impact of fuel prices on the use of renewable and low-carbon fuels is not considered here. However, it should be noticed that applying renewable/low-carbon fuels will lead to higher fuel prices.
The impact of this increase in fuel prices on the energy efficiency of shipping can be estimated by using the empirical evidence found by this study for the relationship between fuel prices and energy efficiency.

The total CO_2 emissions of maritime transport is not only affected by the energy and carbon efficiency of vessels, but also by the demand for shipping. An increase in transport demand can lead to increases in the total fleet size and thus emissions. The fourth IMO GHG study (CE Delft et al., 2020) shows that the average and total emissions of shipping decreased between 2008 and 2018, while total transport work increased. The increase in efficiency thus exceeded the increase in transport demand. Similar findings were presented by Pierre et al. (2019), who found – using empirical data – that global CO_2 emissions of maritime shipping decreased over recent years because of improvements in energy efficiency of vessels (e.g. due to a general decline in speed, technological improvements and improved network design) outweighing the additional emissions due to increased demand for maritime transport.

1.3 Outline of the report

This report is structured as follows:
- Chapter 2 provides an overview of the existing evidence on the relation between fuel prices and energy efficiency of maritime ships, distinguishing between operational and technical energy efficiency.
- Chapter 3 discusses the relevant variables to be included in the econometric analyses of the relationship between fuel prices and energy efficiency of maritime ships. Data to operationalise these variables is one of the issues discussed in this chapter.
- Chapter 4 presents the conceptual models that have been econometrically estimated to assess the relationship between fuel prices and energy efficiency of maritime vessels.
- Chapter 5 presents the findings of the econometric analyses. The results of these analyses have also been used to assess the impact of EU policies (EU ETS, FuelEU Maritime) on the energy efficiency of maritime transport.
- Chapter 6 gives an overview of the main conclusions of the study as well as recommendations for further research.

2 Literature review

2.1 Introduction

In this chapter, we discuss the existing empirical evidence for the relationship between fuel prices and energy efficiency of maritime ships. We do this based on a literature review, considering scientific and grey literature assessing this specific topic. In our assessment, we focus on studies that investigated the impact of fuel prices on energy efficiency of maritime ships. We distinguished between studies that consider the relationship between fuel prices and operational energy efficiency (see Section 2.2) and studies that investigated the impact of fuel prices on technical energy efficiency (see Section 2.3). The main overall conclusions that can be taken from these studies are discussed in Section 2.4.

2.2 Operational energy efficiency

As mentioned in Section 1.2, operational energy efficiency refers to the impact the use of the ship has on energy consumption. There are several measures the crew (or owners) can take to reduce the fuel consumption of a ship during operation. The most common examples of such measures are:
- speed reduction;
- cleaning and maintenance of hull and propellor;
- increasing the load factors and, at fleet level, increasing vessel size;
- adjusting routes for improved loading or to avoid worse weather conditions.

The benefits of such measures on fuel consumption have been broadly studied, e.g. by (CE Delft et al., 2020) and (UMAS, 2023). However, there is limited empirical evidence on the relationship between fuel costs and the extent to which these operational measures are taken. Moreover, the available studies concentrate on speed reduction. In the remainder of this section, we therefore focus on the relationship between fuel prices and the (average) speed of maritime ships.

By reducing sailing speed, energy use and hence CO_2 emissions of the vessel can be significantly reduced. For example, reducing the speed of a Ro-Ro ship by 10 or 40% will reduce its CO_2 emissions by 27 and 78%, respectively (Ammar, 2018). Several researchers empirically assessed the impact fuel prices have on (average) speed of maritime ships. Findings do differ significantly between studies. A few studies find weak empirical evidence for a significant impact of fuel prices on sailing speed. For example, Adlan and Jia (2016b) studied the effect of different factors on vessel speeds, based on AIS data of 607 Very Large Crude oil Carriers (VLCCs) over the period 2013-2015 (resulting in 62,000 weekly observations). One of the explanatory factors included in their model were fuel prices, obtained from the Clarksons database.[3] That study finds a significant relationship between fuel prices and vessel speeds, but this only applies to ballast legs (sailing without cargo). Besides that, they find significant results for the effect on speed of some operational (such as loading conditions) and ship-specific variables (such as age and design speed), but a poor fit of the overall model (represented by a low R^2, indicating a low explanatory power for the model). The authors show that macroeconomic variables (i.e. fuel price and freight rates) have little to no explanatory power for the vessel speed, while speed is influenced by whether the operator is also the cargo owner.

[3] Clarksons Research Portal is a portal for maritime data on shipping and trade.

Adlan and Jia argue that the poor model fit may be due to difficult-to-observe variables, such as local weather and wave conditions and contractual limitations. In another study (Adlan & Jia, 2016b) covering bulk carriers, the same authors find comparable results. In this study they assessed the factors explaining vessel speed based on AIS data of daily sailing speeds between 2011 and 2012 for 18,000 deep sea shipping voyages and fuel prices obtained from the Clarksons database. Overall, they find a poor fit of the estimated model, and macroeconomic variables (i.e. fuel prices, freight rates) have little explanatory power. They conclude that owners do not appear to adjust vessel speeds based on freight market conditions and fuel prices, as argued in classical maritime economic theory. Instead, vessel-specific variables such as age and design speed, as well as operational factors such as loading conditions, show some explanatory power. Again, they argue that the poor model fit may be due to factors outside their model, such as weather conditions and contractual limitations.

Also Adlan et al. (2017) conclude, based on a study investigating the effect of the introduction of emission control areas (ECA) on sailing speeds for a three-year period using daily speed data, that there is no significant evidence for the impact of fuel prices on vessel speed. The empirical analyses performed in this study shows that the introduction of stricter sulphur regulation, which led to the use of more expensive fuels, did not affect vessel speeds once changes in macroeconomic conditions (through spot freight rate) are accounted for. Vessel speeds are instead determined by voyage-specific variables such as whether a vessel is heading towards or away from heavily-trafficked areas or ports of call; whether it is a tanker or cargo vessel; and seasonal weather factors.

There are, on the other hand, several studies that do find a relationship between fuel prices and vessel speeds, thus confirming the classical maritime theory. Acik and Baser (2018) conducted a study into the causal relationship between fuel prices and vessel speed in the dry-bulk market, where the hypothesis is that shipowners reduce vessel speed (negative shock) if there is an increase in fuel price (positive shock). The analysis confirms this causal relationship. However, the opposite causal relation – lower fuel prices resulting in higher sailing speeds – does not hold. An explanation that is given, is that the dry-bulk market has close to perfect market competition, and hence shipowners may not increase their speed and consequently their operating costs, as that moves them away from competitive prices in the market. Another explanation is the optimum point where the least amount of fuel is consumed by a ship. Shipowners are not inclined to increase their speed from that optimum point for small changes in demand.

In addition, Jonkeren et al. (2012) find a significant relationship between fuel prices and sailing speed. Based on a large panel data set with detailed information about dry-bulk trips by inland waterway transport carriers in Northwest Europe[4], they empirically find that freight prices have a positive effect and fuel prices a negative effect on navigation speeds (controlling for shipment size, trip distance, time and month trend and fixed ship-type effects). Furthermore, they find that non-fuel input factors such as labour costs could also play a role in speed choice.

A significant effect of fuel prices on sailing speed was also found by Notteboom and Vernimmen (2009), who investigated the effect of higher bunker costs due to ECAs for container shipping between 2005 and 2007 using daily data. They found that sailing speeds decreased due to higher bunker costs, but that the reaction of liners was delayed.

[4] Although this study considers inland navigation instead of maritime transport, we decided to include it in this review as the study is often referred to in studies covering maritime transport.

As the demand for maritime transport did not decrease, more vessels were employed and average vessel size increased. Operators thus decided to reduce speeds and employ more fuel-efficient vessels (in terms of MJ/tonne-miles). The authors do also argue that the causality between changes in liner service design and bunker costs is somewhat blurred by commercial constraints, which do not always allow speed reductions.

Finally, Lagouvardou et al. (2022) estimated the impact of a bunker levy based on historical data from 2010–2018. For this period, they estimated a model that finds that the implementation of a bunker levy and thus increasing fuel prices would be a successful policy instrument to reduce emissions, as historical data shows (some hints of) correlation between market conditions (fuel price and freight rates) and average operating speeds. This hypothesis was not econometrically tested.

2.3 Technical energy efficiency

The technical energy efficiency of a ship is determined by the design of that ship, and depends on factors like the engine configuration, hull design, auxiliary engines on board, etc. The technical energy efficiency of a ship can be improved by measures like:
- engine configuration or tuning;
- improvements in hull design;
- improvement of energy equipment on board for example for pumps, boilers and waste heat recovery;
- use of wind and solar power.

Several relevant topics related to the technical energy efficiency of maritime ships have been investigated (non-exhaustive):
- The **CO_2 saving potential and/or energy reduction potential of technical energy efficiency measures**; for example, CE Delft et al. (2020) estimated the CO_2 reduction potential for more than fifteen technical measures. Similar types of exercises have been carried out by studies like UMAS (2021) and DNV (2022).
- The **theoretical optimal implementation level of technical energy efficiency measures;** based on cost-benefits considerations. This has, for example, been done by CE Delft et al. (2020) and CE Delft (2011) for CO_2 reducing technologies. Lindstad et al. (2015) set up a cost-based model to estimate the most cost-effective measure to comply with the ECA/SECA requirements.
- The **extent by which technical energy-efficiency measures are implemented**; for example, Rehmatulla et al. (2017) investigated the uptake of technical efficiency measures using a comprehensive survey among about 200 shipping companies. They find that within each category of technical energy efficiency measures (e.g. engine optimisation, resistance reducing measures, etc.) there are a handful of options that clearly have the highest implementation rate amongst the companies (but also that these are the measures that have the smallest energy-efficiency gains at ship level). Other studies assessing the implementation rate of specific technical efficiency measures include CE Delft (2011), Rojon and Smith (2014), and DNV GL (2014).
- The **factors driving investments in fuel-efficient technologies**; for example, Longarela-Ares et al. (2023) find based on an empirical study using a sample of 658 individual bulk vessels that the gap of a vessel between its technical emissions and EEDI requirements and (absence of) split incentives are the parameters with the greatest influence in the decision to invest in technical (or operational) measures for increasing the energy efficiency.

In contrast to the topics mentioned earlier, the impact of fuel prices on the implementation of technical energy-efficiency measures are very scarcely investigated. From a theoretical point of view, it can be argued that higher fuel prices make fuel-efficient ships more attractive, because energy efficiency reduces the total cost of ownership. The higher investment costs for these ships (e.g. fuel-efficient hull designs are more expensive to build due to factors like higher steel costs and higher labour costs) can be earned back over the lifetime of the ship by lower fuel costs. Conversely, when fuel costs are relatively low, the capital expenditures are a larger share of the total costs of ownership and ship owners may opt for a cheaper, less efficient design.

Rehmatulla et al. (2017) included the issue in their survey among shipping companies. The respondents to this survey indicated that low fuel prices lead to reduced investments in energy saving measures, but the significance of this statement has not been empirically tested.

CE Delft (2016b) performs a graphical comparison of the development of fuel prices[5] and the relative design efficiency of ships.[6] Based on ship-specific data on the design speed, deadweight tonnage (dwt) and the main engine's power and dimensions[7], the researchers have estimated the relative design efficiency for all ships that have entered the fleet since 1960. The development of the average relative design efficiency over time was plotted (for bulker, tanker and container ships separately) against the development of fuel prices over time. From these graphical comparisons, it was concluded that for all three ship types the fuel prices seem to be a driver of efficiency improvements, as large increases in fuel prices were followed by large improvements in fuel efficiency of new ships. The lag between the two was estimated to be between four and eight years. The authors presented two possible explanations for this time lag. First, it takes a few years before ship owners translate fuel price increases into higher fuel price projections. Second, an increase in fuel prices first triggers studies into more fuel-efficient designs, which take time to be completed, ordered and then built. The study also finds that the reaction to fuel price increases in the 2000s was much less pronounced than in the 1980s. A possible explanation mentioned in the study was a moderating effect of freight rates. These were rather constant in the 1970s, while they show an increasing trend in the 2000s. As higher freight rates are expected to lead to less pressure to improve fuel efficiency[8], this effect may explain the less pronounced effect of fuel prices on design efficiency in the 2000s. However, these conclusions were based on simple graphical comparisons and expert judgement.

5 Using the average price of crude oil as proxy for the real heavy fuel oil price (both are expected to be strongly correlated).

6 The relative design efficiency is defined as the EIV of the ship divided by the EEDI reference line value of that ship. The Estimated Index Value (EIV), which is a simplified version of the EEDI, is an indicator calculating the design efficiency of a ship based on input factors like the specific fuel consumption figures of the main and auxiliary engines, the load capacity and the design speed. The EEDI reference line value is a baseline design efficiency set by the IMO for the various maritime ship segments (i.e. bulker, tanker, container ships), taking into account the load capacity of the ship. For more information on the EVI and EEDI reference line value, see Section 3.2.2.

7 These data have been taken from the Clarksons World Fleet Register (for ships in the 2015 fleet) and the IHS Maritime World Register of Ships (for ships that were scrapped before 2015).

8 For example, when freight rates are high, owners queue up to order ships, lowering the incentive of shipyards for innovative designs and thus keeping efficiency low.

2.4 Conclusions

Our analysis of the literature on the relationship between fuel prices and energy efficiency of maritime ships shows that only a limited number of researchers have studied this topic. Most studies have been conducted on the effect of fuel prices on sailing speeds, with varying results. Some of these studies have shown a causal relationship between these two factors, others have not. An important conclusion is that sailing speed is affected by non-financial variables as well, like contractual aspects between charterers and ship owners, sailing routes and weather conditions.

With respect to technical energy efficiency, we have not identified empirical studies confirming a causal relationship between fuel prices and technical energy. There are a few studies showing some evidence for such a relationship, but empirical confirmation is lacking.

3 Description of relevant variables

3.1 Introduction

In order to empirically analyse the relationship between fuel prices and energy efficiency of maritime vessels we have identified the relevant variables and assessed to what extent data is available to operationalise these variables. A detailed discussion is available in Annex A. In this chapter we only discuss the variables used for the two econometric models used in this study. The first model assesses the relationship between fuel prices and the technical energy efficiency of maritime ships, while the second model assesses the relationship between fuel prices and operational energy efficiency (i.e. vessel speed). More details of both models can be found in Chapter 4.

In the discussion of relevant variables, we distinguish:
- *Dependent variables*, i.e. the variables that are being studied, in this case technical energy efficiency of vessels and vessel speed.
- *Independent variable*, i.e. the variable for which we want to explain the effect on the dependent variable(s). In this study, fuel price is the independent variable.
- *Control variables*, i.e. other variables which may affect the value of the dependent variable(s). Including these variables in the econometric model(s) is required to isolate the effect of fuel prices on technical energy efficiency or speed of ships.

In the remainder of this chapter (Sections 3.2 to 3.4 respectively), we will discuss the three types of variables used for the modelling.

3.2 Dependent variables

3.2.1 Technical energy efficiency

Estimated Index Value (EIV)

The Estimated Index Value (EIV) is a first potential data source suited for our model as an approximation for technical energy efficiency. The EIV provides an estimation of the technical energy efficiency of vessels. The EIV is a simplified form of EEDI (explained in more detail below). In contrast to the EEDI, the EIV can be calculated based on publicly available data. For this reason, EIV can be estimated for vessels built before 2013 which allows for longer time periods suiting our modelling purposes.

The EIV is given by the following formula (MEPC, 2012):

$$EIV = 3.1144 \cdot \frac{190 \cdot \sum_{i=1}^{NME} P_{MEi} + 215 \cdot P_{AE}}{Capacity \cdot V_{ref}}$$

With

3.1144	=	the CO_2 emission factor of fuel (g CO_2/g fuel oil);
190	=	the specific fuel consumption of main engines (g/kWh);
215	=	the specific fuel consumption of auxiliary engines (g/kWh);
PME(i)	=	75% of the total installed main power (MCRME) (kW), where i reflects the number of main engines;
PAE	=	the auxiliary power calculated according to Sections 2.5.6.1 and 2.5.6.2 of ; the annex to MEPC.212(63) (kW);
Capacity	=	70% of dead weight tonnage (dwt) for container ships and 100% of dwt for other ship types (tonnes);
Vref	=	speed as indicated in the database (knots). As discussed in a previous study (CE Delft, 2017), the databases do not specify at which percentage of MCR speed is measured, though it generally seems to be design speed (100% MCR)[9].

As shown in the formula, the EIV uses fixed values for CO_2 factor for fuel as well as the fuel consumption of engine types. This enables the EIV to be calculated for many vessel types. A drawback is that the improvements in fuel consumption of engines are not considered. The EIV index can be improved by:
- reducing the installed engine power of vessels keeping all else equal;
- increasing the capacity keeping all else equal;
- increasing the speed keeping all else equal.

In other words, for a new ship to improve its EIV, it needs to transport more and/or faster, or transport as much but using less energy. The EIV uses fixed values for the fuel consumption of ship engines. In practice, engine efficiency has improved over time resulting in lower fuel consumption levels. Due to this higher engine efficiency vessels require relatively less engine power for the same vessel characteristics. As a result, it is likely that there is an autonomous improvement of the EIV over time. We will discuss in Chapter 4 and Chapter 5 how this effect is captured in the models that we applied.

The EIV data can be calculated from publicly available data. CE Delft (2015) has calculated EIV values based on data from Clarksons for vessels built before 2013. We have extended this dataset by also calculating the EIV values for vessels built after 2013 based on data from Clarksons. In total we have a dataset of about 28,000 vessels.

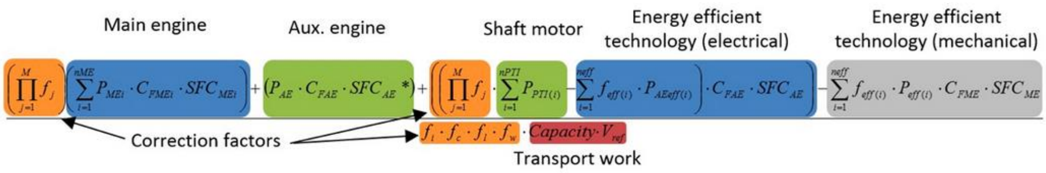
Energy Efficiency Design Index (EEDI)

The Energy Efficiency Design Index (EEDI) is the official index for the technical energy efficiency as used by the IMO. As of 2013, new ships are required to have an EEDI, which should prove that the ship is more efficient than a minimum standard. The EEDI is only applicable to new-builds and vessels built before 2013 do not have an EEDI.

The formula for the EEDI takes the same form as the EIV, dividing technical CO_2 emissions by capacity and speed, but introduces several additional ship specific factors. Foremost, the fuel specific fuel consumption is ship specific and not based on fixed values. Furthermore, there are correction factors for ship specific design elements, capacity limiting factors due to regulations and innovative energy efficiency technologies (MARPOL, ongoing). This allows, for example, ice-class ships to have larger engines without exceeding EEDI reference lines. The EEDI formula is shown in Figure 2.

[9] For consistency reasons we have opted to use the same source of speed compared to the previous studies.

Figure 2 - EEDI formula



Source: IMO (2024)

With the following parameters (MEPC, 2018):

P = Installed engine power, with division to main engines (PME), Auxiliary engines (AE), Shaft motor (PTI).

C_F = Conversion factor between fuel consumption and CO_2 emission for main engines (PME), Auxiliary engines (AE).

SFC = Specific Fuel Consumption of main engines (PME) and Auxiliary engines (AE)

Capacity = 70% of dead weight tonnage (dwt) for container ships and 100% of dwt for other ship types (tonnes).

Vref = design speed measured at 75% of the maximum continuous rating (MCR) of the engine.

f_j = Ship specific design elements.

eff = innovative energy efficiency technology.

Due to inclusion of additional ship specific information and correction factors the EEDI cannot be calculated from public sources. It is also difficult to compare the results directly with the outcomes for the EIV, as the EIV does not include such ship specific factors. Another factor is that vessel speeds in EEDI are measured at 75% of the maximum continuous rating (MCR) of the engine, while the data for EIV uses 100% MCR. In general, the EIV is on average higher than the EEDI, meaning that ships are generally more fuel efficient than the EIV suggests (CE Delft, 2017).

IMO regulations stipulate that vessels have to reduce their EEDI compared to 2000-2010 reference levels. The reduction targets, which are sharpened over time, are shown by Table 1.

Table 1 - EEDI reduction targets

	Phase 0	Phase 1	Phase 2	Phase 3
	1 Jan 2013 - 31 dec 2024	1 Jan 2015 - 31 Dec 2019	1 Jan 2020 - 31 dec 2024	1 Jan 2025 and onwards
General reduction targets compared to reference line*	0%	10%	20%	30%

* Specific reduction targets and reference lines vary by vessel type and size.

The EEDI score of individual vessels is available at the IMO. Transport & Environment, who have access to the EEDI database, have shared this information (anonymised) for this report. In total the EEDI score is available for about 8,000 vessels within the categories of dry bulkers, tankers and containerships. For each vessel, information on the EEDI phase, the EEDI score and the DWT is available.

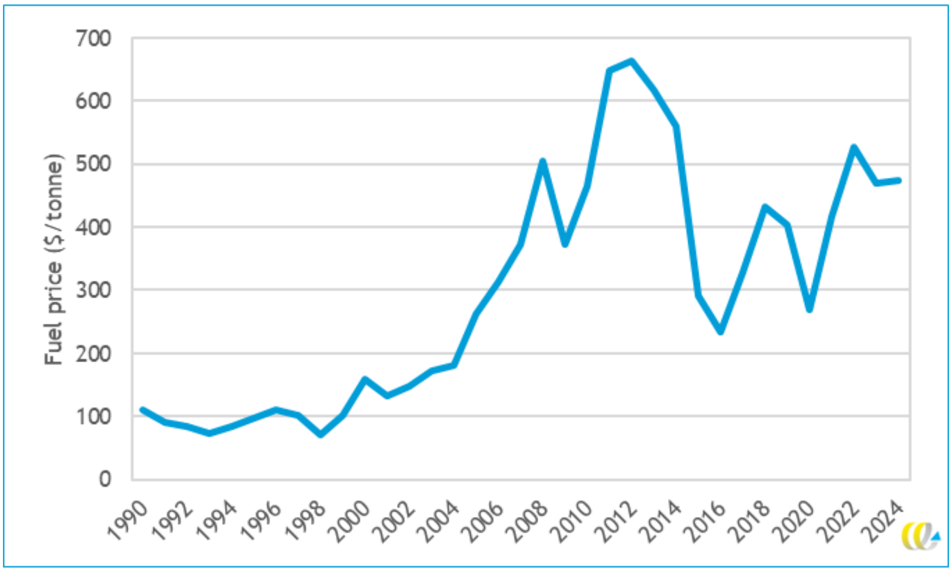
3.2.2 Operational energy efficiency

With respect to operational energy efficiency, only data on sailing speeds is available, as is discussed in Annex A. This is in line with other empirical assessments found in the literature (see Section 2.2). For sailing speed, we rely on aggregated monthly data by vessel type from Clarksons. This data is available from the first of January in 2012 and is based on AIS observations of individual vessels. The data is available for four size categories of bulker vessels, five size categories of tankers and six size categories of container vessels. In total we thus distinguish fifteen classes of vessels.

3.3 Independent variable: fuel prices

The main data source of fuel prices is provided by Clarksons, which is also used by most studies in the literature review (see Chapter 2). The data is available for a long period, starting in 1990 with weekly observations. We take prices for heavy fuel oil (HFO) in Singapore, which has the best data availability, as proxy for development in fuel price for all ports and fuel types. For Model 1 we use annual fuel price data starting in 1990, while for Model 2 we use monthly fuel price data starting in January 2012 in line with sailing speed data.

Figure 3 - Average yearly fuel prices (HSFO 380cst Bunker Prices (3.5% Sulphur), Singapore), 1990-2024



3.4 Control variables

3.4.1 Overview of potentially relevant control variables

There are several control variables that are useful to include, though the exact necessity depends on the dependent variable and the conceptual model (see Chapter 4). An overview of potentially relevant control variables is provided in Annex A. In that annex, we also assessed the relevance and possibility to include the various variables into one of the two econometric models (i.e. with sailing speed or technical energy efficiency as dependent variables). In this section, we only discuss the variables that have been included in one (or both) models in more detail.

Differences that only refer to time (such as weather, the economy) that apply to all vessel types could be controlled for by using time-fixed effects. This means that time is added as a variable, accounting for changes over time that apply to all vessels. This is, however, more difficult for variables that differ between vessel types.

3.4.2 Charter rates and freight rates

There are several methods available to measure freight rates or earnings. Which indicator is most relevant depends on the contract form in each shipping market. The most common forms are:
- own ownership;
- time charters (ship is rented for a period of time);
- voyage charters (ship is rented for specific voyage);
- bareboat (ship is rented without crew).

For each contract form there can be various other types of clauses which further determine which costs are borne by the vessel owner and the charterer. In general, the longer a contract duration the higher the amount of costs borne by the charterer. Fuel costs, an important determinant of shipping costs, can be borne by the vessel owner as well as by the charterer. In case the fuel costs are borne by the charterer, the charter rates paid to the vessel owner will be significantly lower. In general, for voyage charters fuel costs are borne by the vessel owner (and hence included in the freight rates), while for time chartering and bareboat these costs are often borne by the charterer. For own ownership the costs are logically born by the owner. Furthermore, sailing speeds and corresponding fuel consumption is often stipulated in the contracts for time chartering[10], and as a result the sailing speed is constant during the contract duration under normal circumstances. The impact of fuel prices on sailing speed will therefore be low (on the short term) for these types of contracts.

The extent to which the various contract forms are used differs between shipping segments as well as over time. Voyage chartering is more suited to volatile flows of goods, while time chartering is suited for more long-term flows of goods. In container shipping, own ownership and time chartering are the common methods of employments [11], while for dry and liquid bulk voyage and time chartering are most common methods of employment.[12] In terms of rates, spot rates (term for voyage charter rates) are more volatile as there are higher risks for vessel owners.

We make use of time charter rates available on Clarksons for our main analyses. Time charters are common in bulker markets and the data availability is good. For container transport, where time chartering is less common, time charter rates are available for various size classes. As shown by Zhang and Zeng (2015) spot rates and time charter rates are often related and follow similar patterns. We expect that development in time charter rates provide a good proxy for the balance between demand and supply for market segments where trip charter or spot rates are (mainly) used as well. Therefore, it seems that (the development in) time charter rates could be applied as control variable for all ship categories in the econometric analysis.

---

10 www.handybulk.com/ship-speed-and-consumption-warranty-in-time-charter-party/

11 www.hellenicshippingnews.com/record-high-container-order-book-of-7-54-million-teu-signals-significant-change/

12 www.handybulk.com/dry-bulk-chartering/

As we will discuss in Chapter 5, for the model in which we study the relationship between fuel prices and sailing speed, we carry out a sensitivity analysis with container freight rates instead of charter rates. Data on freight rates are collected on a weekly basis from active shipbrokers. Data is available on Clarksons from 1990 for main vessel types including several size classes. In total we distinguish fifteen different vessel type and size combinations.
For Model 2 we make use of monthly data starting from January 2012. Missing data has been estimated using inter- and extrapolation based on years and vessels for which data is available. As discussed, time chartering is less relevant for container vessels. For this reason, we use the China Containerized Freight Rate Index (CCFI) for a sensitivity analysis. Data is available on Clarksons and starts from March 2003.

4 Methodology

4.1 Introduction

Based on our analysis in the previous chapters, we have identified three econometric models through which we can empirically study the relationship between fuel prices and the energy efficiency of vessels:
- Model 1.1: a model including the technical efficiency (EIV) of new-build ships;
- Model 1.2: a model including the technical efficiency (EEDI) of new-build ships;
- Model 2: a model including vessel speeds as a proxy for the operational energy efficiency of vessels.

In the remainder of this chapter, we will explain the models in more detail.

4.2 Model 1: Fuel prices and technical efficiency of new-build ships

Model 1.1: Fuel prices and the EIV of new-build ships

With Model 1.1 we study the relationship between yearly bunker fuel prices and the technical efficiency of new-build ships between 1990 and 2024 as measured by the Estimated Index Value (EIV). The Ordinary Least Squares (OLS)[13] regressions that we have carried out to study the relationship between the EIV of new-build ships and fuel prices, include the variables as presented in Table 2.

Table 2 - Model 1.1: variables OLS regression

Variable	Name	Description	Type	Source
Dependent	EIV	Efficiency index (EIV) of new-build ship; at individual ship level	Continuous	EIV database
Independent	Fuel price	Yearly average in $; HSFO 380cst Bunker Prices (3.5% Sulphur), Singapore[14]	Continuous	Clarksons research shipping intelligence network
	Charter rate	Yearly averages in $; by vessel type and deadweight class	Continuous	Clarksons research shipping intelligence network
	Year	Dummy variables for the year or period the ship was built	Dummy	EIV database
	Vessel type	Dummy variables for the three vessel types: bulk carriers, container ships, tankers	Dummy	EIV database

[13] An Ordinary Least Squares (OLS) regression is a common technique for estimating coefficients of linear regression equations which describe the relationship between one or more independent variables and a dependent variable.

[14] Note that in our model also ships not running on HSFO are evaluated against HSFO bunker prices. We assume that other fuels follow a similar price path and therefore HSFO can be seen as a proxy for other fuel prices.

Table 3 shows the descriptive statistics of the main variables of Model 1.1. It shows that the EIV efficiency of new-build ships is relatively strongly skewed with a longer right tail, indicating a large number of outliers (new-build ships with a high EIV and thus low technical efficiency). Fuel prices are slightly positively skewed, but nearly normally distributed with thin tails and thus a relatively low number of outliers. Although a similar distribution to that of fuel prices would be expected, the distribution of charter rates is more strongly positively skewed. This can be explained by the fact that the charter rate variable contains different charter rate classes for different ship types and deadweight categories, thus entailing more outliers. Note that applying log-transformations to these variables – as we will do in the econometric models presented in the next chapter - forces a more normal distribution on the data.

Table 3 - Descriptive statistics Model 1.1 (new-build ships), 1990-2024

	Mean	Median	Std. deviation	Min	Max	Skewness	Obs.
EIV	10.53	6.48	9.94	0.31	250.86	5.59	27,267
Fuel price ($/tonne)	331.44	352.37	169.20	83.31	614.69	0.20	27,267
Charter rate ($/day)	20,693.09	16,606.59	13,852.45	5,137.06	117,754.50	2.63	27,267
Container ships							6,006
Bulk carriers							11,474
Tankers							9,787

As it will take some years before the efficiency of new-build ships increases as response to higher fuel prices (and other economic variables) we included lags in our models to account for this delayed effect. In an earlier study the lag was estimated to lie between four and eight years (CE Delft, 2016b). Note that – as data on fuel prices and charter rates are only available from 1990 onwards - when applying lags to fuel prices and charter rates, the start date of the model depends on the lags chosen. For example, when the lag used for fuel prices is six years, only new-build ships from 1996 onwards can be considered.

In order to account for possible time-effects (e.g. introduction of new IMO or EU policies, but also autonomous efficiency improvements), time dummy variables are included in the model for specific periods of time.

Model 1.2: Fuel prices and the EEDI of new-build ships

With Model 1.2 we study the relationship between yearly bunker fuel prices and the technical efficiency of new-build ships between 2010 and 2024 as measured by the Energy Efficiency Design Index (EEDI). The EEDI is a more realistic indicator of the actual technical energy efficiency of new-build vessels than the EIV, but as explained in Section 3.2.1 the dataset for the EEDI is less extensive as for the EIV. Therefore, we have chosen to use the EIV as the independent variable in the main analysis of fuel prices on technical energy efficiency of vessels and using the models based on the EEDI as sensitivity analysis. Among other things, estimating Model 1.2 allows us to test the robustness of the empirical evidence found by the estimation of Model 1.1.

As for Model 1.1, we have carried out OLS regressions to study this relationship. The variables used are presented in Table 4. In this model we account for possible time- and EEDI policy-effects by including dummy variables for the different EEDI phases new-build ships had to comply with.

Table 4 - Model 1.2: variables OLS regression

Variable	Name	Description	Type	Source
Dependent	EEDI	Energy Efficiency Design Index (EEDI) of new-build ship; at individual ship level	Continuous	IMO website[15]
Independent	Fuel price	Yearly average in $; HSFO 380cst Bunker Prices (3.5% Sulphur), Singapore[16]	Continuous	Clarksons research shipping intelligence network
	Charter rate	Yearly averages in $; by vessel type and deadweight class	Continuous	Clarksons research shipping intelligence network
	EEDI phase	Dummy variables for the different EEDI policy phases: Non-mandatory, Phase 0, Phase 1, Phase 2, Phase 3	Dummy	IMO website[15]
	Vessel type	Dummy variables for the three vessel types: bulk carriers, container ships, tankers	Dummy	IMO website[15]

Table 5 shows the descriptive statistics of the main variables of Model 1.2. It shows that the EEDI efficiency of new-build ships is less skewed and has a thinner right-tail than the EIV (as shown in Table 3), indicating a smaller number of outliers. This can be explained by the fact that the EEDI of new-build ships stretches over a shorter period (2014-2024 rather than 1990-2024). Fuel prices are slightly positively skewed, but nearly normally distributed with thin tails and thus a relatively low number of outliers. The distribution of charter rates is, again, more strongly positively skewed and has heavy tails.

Table 5 - Descriptive statistics Model 1.2 (new-build ships), 2010-2024

	Mean	Median	Std. deviation	Min	Max	Skewness	Obs.
EEDI	6.13	4.11	5.08	1.458	69.11	2.88	7,992
Fuel price ($/tonne)	341.48	352.37	101.75	206.69	614.69	0.46	7,992
Charter rate ($/day)	14,835.38	12,342.11	11,317.49	5,232.66	117,754.50	5.04	7,992
Container ships							1,403
Bulk carriers							3,858
Tankers							2,731

15 The information on EEDI values has been retrieved by T&E who have access to the official database on the IMO website.

16 Note that in our model also ships not running on HSFO are evaluated against HSFO bunker prices. We assume that other fuels follow a similar price path and therefore HSFO can be seen as a proxy for other fuel prices.

Literature

As discussed in Section 2.3, literature on the relationship between fuel prices and the technical energy efficiency of ships is scarce. In an earlier study, a descriptive analysis was carried out in which a correlation between fuel prices and EEDI efficiency of new-build ships was suggested (CE Delft, 2016b). No regression analysis was performed to prove the causality of this relationship.

4.3 Model 2: Fuel prices and vessel speeds

Model

The variables for the econometric model, a panel data multiple regression model, are given in the following table. This dataset is a panel dataset, which includes both a cross-section and time element, with the ship type as identifier for the cross-section, and a time frequency of monthly data.

Table 6 - Model 2: variables panel data multiple regression

Variable	Name	Description	Type	Source
Dependent	Average sailing speed	Monthly data; aggregated by vessel type	Continuous	Clarksons research shipping intelligence network
Independent	Fuel price	Yearly average in $; HSFO 380cst Bunker Prices (3.5% Sulphur), Singapore	Continuous	Clarksons research shipping intelligence network
	Charter rate	Monthly averages in $; by vessel type and deadweight class	Continuous	Clarksons research shipping intelligence network
	Freight rate	Composite Containerised Freight Rate Index (CCFI), global and for China-EU	Index	Clarksons research shipping intelligence network
	Seasonal effect	Dummy variables for winter, spring, summer, fall	Dummy	–
	Vessel type	Dummy variables for the three vessel types: bulk carriers, container ships, tankers	Dummy	Clarksons research shipping intelligence network

Table 7 presents the descriptive statistics of the variables included in Model 2, with vessel speed as the outcome variable. This model contains average data on each of the variables on a monthly basis. Vessel speed is measured in knots, with a relatively normal distribution. It is slightly positively skewed. Vessel speed differs quite distinctly between the various ship types. Fuel prices are also slightly positively skewed, but fairly normally distributed. Charter rates are positively skewed with a long right-tail. Similarly to Model 1, the lack of normal distribution is explained by the inclusion of average data across varying ship types and dwt categories. Freight rates are measured as an index, which differs over time but is the same for all dwt categories of container ships. The data is fairly normally distributed, although slightly positively skewed. For estimation, the variables are log-transformed, improving the normal distribution of the variables.

Table 7 - Summary statistics for Model 2 (vessel speed)

	Mean	Median	Std. deviation	Min	Max	Skewness	Obs.
Vessel speed	13.1	11.9	2.0	10.7	17.8	0.609	2,235
Fuel price ($/tonne)	376.3	352.5	125.7	141.7	666.3	0.383	2,235
Charter rate ($/day)	19,607	13,586	22,877	4,202	202,151	4.97	2,235
Freight rate, global (index)	1,227	948	718	642	3,511	2.06	888
Freight rate, China-EU (index)	1,698	1,141	1,287	635	5,721	2.03	888
Container ships							894
Bulk carriers							596
Tankers							745

Based on these variables, different models have been estimated. For example, we have created a model with a dummy for the three main categories of vessel types (tankers, bulkers, containers), creating separate models for the three main categories. A model with all types of vessels included has been used to assess the general relationship between fuel prices and average sailing speed, whereas a model for a specific vessel type can be used to infer about the relationship between these variables for that specific vessel type.
The variables on fleet size and average vessel age of the fleet, are expected to be reflected in the vessel type dummies and simply due to the panel dimension of the data (in which there is both a cross-section and time element), and therefore, have not been included separately.

Data availability

As discussed in the previous chapter, Clarksons provides data on average vessel speed from 2012 to 2024 for a selection of vessel types, resulting in 144 time periods that can be used in our model. As discussed in Section 3.4, time charter rates is an important control variable. Based on the analysis of the data availability of this variable – shown in Table 24 in Annex A.4.2Table 14 – we concluded that there is sufficient data for sixteen types of vessels (tankers, bulkers, and containers; various size classes per vessel type), leading to a total of 2,235 observations. The data availability of the other variables was also sufficient (see Chapter 3).

Literature

Several studies have already investigated the effect of fuel prices on sailing speeds. Some of these studies have shown a causal relationship between these two factors, others have not. Compared to these existing studies, our model has two pros and one main con. One pro is that most relevant studies, such as Adlan and Jia (2016a) and Adlan and Jia (2016b), study a shorter time period. As we studied a longer period of time, this could provide the opportunity to observe more long-term trends and effects. Another pro of our approach, is that most other studies have only focused on one or a few types of vessels. As we studied sixteen different types of vessels, this may lead to new insights.

The main con of our approach is that we use aggregated data at vessel type level.
A potential risk when using these data, is that we exclude important variables that affect sailing speeds at an individual ship-level from our model. Examples are vessel age, vessel size, design speed, and cargo size (typically included in studies at vessel/voyage-level), contractual aspects between charterers and ship owners, sailing routes, and weather circumstances (also not included in studies at vessel/voyage level). Adlan and Jia (2016a) and Adlan and Jia (2016b), who used data at vessel/voyage-level and thus include more detail, have – although some significant results were found - already shown that it is difficult to fit a model with high explanatory power due to the inability to include such variables in the model.

5 Results

5.1 Introduction

This chapter describes the results of the econometric models (Model 1.1, Model 1.2, and Model 2) that we described in the previous chapter. Section 5.1 and 5.2 each describe the main findings, followed by a more detailed description of several sub-models. The overall conclusions that can be drawn from these findings are presented in Chapter 6.

5.2 Model 1: Fuel prices and technical efficiency of new-build ships

5.2.1 Main findings

In order to study the relationship between bunker fuel prices and the technical energy efficiency of new-build ships, we have studied both the EIV (Model 1.1) and EEDI (Model 1.2) efficiency of new-build ships and analysed different sub-models – which we will discuss in more detail in the next section. Overall, the results show that the models have (highly) statistically significant outcomes and a proper fit.

Note – as discussed in Chapter 3 - that the EIV indicates the technical efficiency of new-build ships, which does *not* account for efficiency improvements of the motor. The EEDI, on the other hand, does include efficiency improvements of the motor.

In general, we see that higher bunker fuel prices have a negative effect on both the EIV and the EEDI – meaning the technical energy efficiency of new-build ships improves.
We analysed Model 1.2 (including the EEDI) as a sensitivity analysis for the results related to Model 1.1 (including the EIV), showing some indication that the relationship between the EEDI and fuel prices could be less strong than the relationship between the EIV and fuel prices. We see two possible explanations for this difference between both types of models. First, it is likely that the implementation of policy instruments by the IMO and EU over the last decade has had an effect on the relationship between fuel prices and the technical energy efficiency of new-build ships. As Model 1.1 covers a much longer time period (i.e. 1990–2024), it also takes into account the probably stronger impact of fuel prices on technical energy efficiency for the earlier years (before the implementation of the EU and IMO policies). Secondly, specific differences in design of the EIV and the EEDI may explain part of the variance between the results of Model 1.1 and Model 1.2 (see Section 5.2.3 for more details).

Moreover, the results show that the relationship between fuel prices and technical energy efficiency (as measured by the EIV) varies between ship types: the technical energy efficiency of tankers is less sensitive to fuel price changes than container ships, while the price effect is close to zero for bulk carriers. Higher charter rates (used as proxy for economic conjuncture) have a negative effect on the technical energy efficiency of new-builds as well – suggesting that better economic circumstances (and hence more demand for shipping services) accommodate investments in more energy efficient new ships.
This relationship is also different for different ship types: the EIV of tankers is much *more* sensitive (about four times as sensitive) to charter rate changes than container ships, while the EIV of new-build bulk carriers is slightly *less* sensitive to charter rate changes compared to container ships.

Finally, in Model 1.1 the time dummies indicate that efficiency of new-build ships between 1995 and 2014[17] was worse (hence, having a *higher* EIV) compared to the period 2015-2024. The latter result may be explained by the introduction of governmental policies (e.g. the EEDI) to incentivise the improvement of technical energy efficiency of new-build vessels. Model 1.2 provides some indication that the EEDI efficiency improves as targets became stricter, but these effects could not be isolated from other (potential) time-effects.

In the remainder of this section, we will dive deeper into the data and sub-models that we used and the detailed results.

5.2.2 Model 1.1: Detailed results

With Model 1.1 we study the relationship between yearly bunker fuel prices and the technical efficiency (EIV) of new-build ships between 1990 and 2024. In order to study different effects and validate the robustness of the results, we analysed several (sub-)models:

- **Model 1.1a**: (log) lagged variables. This model accounts for a delayed effect of fuel prices and charter rates on the EIV efficiency of new-build ships. The results of this model can be interpreted as relative changes (e.g. a 1% increase in fuel price leads to an x% change in EIV). Note that this model considers fuel prices and charter rates in *a specific year*, whereas investors (or, ship owners) will typically look at trends rather than incidental changes. Therefore, the yearly fuel prices and charter rates in this model should be interpreted as being a proxy for these trends.
- **Model 1.1b**: lagged variables + fuel price interaction effects. This model accounts for a delayed effect of fuel prices and charter rates (at a given moment in time) on the EIV efficiency of new-build ships, while studying whether there is *a different relationship between fuel prices and EIV efficiency for different types of ships* (tankers, bulk carriers, and container ships).
- **Model 1.1c**: lagged variables + charter rate interaction effects. This model accounts for a delayed effect of fuel prices and charter rates (at a given moment in time) on the EIV efficiency of new-build ships, while studying whether there is *a different relationship between charter rates and EIV efficiency for different types of ships* (tankers, bulk carriers, and container ships).
- **Model 1.1d**: (log) x-year average variables. This model accounts for a delayed effect of average fuel prices and charter rates *over a multi-year period* on the EIV efficiency of new-build ships. By considering averages over a multi-year period, this model accounts better for the behaviour of investors (or, ship owners) than Model 1a. The results of this model can be interpreted as relative changes.

Table 8 presents the results of four different econometric models for new-build ships. These are the most relevant variables referred to in the table:

- *fuel price y-6*: average yearly bunker fuel price 6 years before the ship was built;
- *charter rate y-2*: average yearly charter rate 2 years before the ship was built;
- *fuel price 14-year*: average bunker fuel price over the 14-year period before the ship was built;
- *charter rate 4-year*: average charter rate over the 4-year period before the ship was built;
- *D_tanker*: dummy indicating the ship type is tanker;
- *D_bulk carrier*: dummy indicating the ship type is bulk carrier;
- *D_1995-1999*: time dummy indicating the ship is built between 1995-1999;

[17] The dummy for 1990-1994 is omitted as there are no observations in this period due to 6-year lag applied to fuel prices.

- *D_2000-2004*: time dummy indicating the ship is built between 2000-2004;
- *D_2005-2009*: time dummy indicating the ship is built between 2005-2009;
- *D_2010-2014*: time dummy indicating the ship is built between 2010-2014.

Hereafter, in the detailed discussion of the sub-models, we will explain how we have come to the selected lags for the fuel price and charter rate variables.

The dataset contains three different ship types: tankers, bulk carriers, and container ships. We included dummy variables for tankers and bulk carriers (*D_tanker* and *D_bulk carrier*, respectively), meaning that container ships are the reference. The coefficients in Table 18, therefore, have to be interpreted as compared to container ships.

In order to account for the time effects (such as the efficiency of new-build ships improves over time due to autonomous developments), we tested with different time dummies: for each year and for 2-year, 3-year, 4-year, and 5-year periods. The results showed that the shorter the period of the time dummy, the higher the significance of the dummies (i.e. specific years highly predict changes in the EIV), but also the higher the multicollinearity of these variables (i.e. the time dummies are highly correlated with changes in fuel prices and charter rates). When using the 5-year period dummies, the models show little signs of multicollinearity. Therefore, we applied 5-year period dummies in our models (in Table 8: *D_1995-1999*, *D_2000-2004*, *D_2005-2009*, *D_2010-2014*). Note that D_1990-1994 is omitted because of the lags that we used (using a 6-year lag means that for ships delivered in 1996, we look at data in 1990). Moreover, we left *D_2015-2019* and *D_2020-2024* out of the model, so that the period 2015-2024 serves as the reference period (most relevant policies entered in this period).

Table 8 - Results OLS regressions Model 1.1 (EIV of new-build ships)

	1.1a: log lagged variables	1.1b: lagged variables + fuel price interaction effects	1.1c: lagged variables + charter rate interaction effects	1.1d: log x-year average variables
Dependent variable:	Log(EIV)	EIV	EIV	Log(EIV)
Constant	8.057047 *** (0.1033)	25.25408 *** (0.3550)	19.59226 *** (0.3427)	11.66258 *** (0.1678)
Log(Fuel price y-6)	-0.2643585 *** (0.0124)			
Log(Charter rate y-2)	-0.4147249 *** (0.0057)			
Fuel price y-6		-0.0262092 *** (0.0009)	-0.0060055 *** (0.0006)	
Charter rate y-2		-0.0000965 *** (0.0000)	-0.0000813 *** (0.0000)	
Log(Fuel price 14-year)				-0.6016417 *** (0.0235)
Log(Charter rate 4-year)				-0.5932854*** (0.0067)
D_tanker	-0.8881598 *** (0.0077)	-14.76595 *** (0.2274)	-4.003757 *** (0.2636)	-0.8142296 *** (0.0080)
D_bulk carrier	-1.29051 *** (0.0076)	-20.30461 *** (0.2318)	-14.31856 *** (0.1996)	-1.16671 *** (0.0078)
D_tanker * Fuel price y-6		0.0199615 *** (0.0008)		
D_bulk carrier * Fuel price y-6		0.0255112 *** (0.0008)		
D_tanker * Charter rate y-2			-0.0002439 *** (0.0000)	
D_bulk carrier * Charter rate y-2			0.0000208 *** (0.0000)	
D_1995-1999	0.386517 *** (0.0191)	3.794752 *** (0.2616)	4.564243 *** (0.2622)	
D_2000-2004	0.197627 *** (0.0196)	2.615101 *** (0.2583)	3.493128 *** (0.2587)	0.1096487 *** (0.0274)
D_2005-2009	0.5998618 *** (0.0146)	4.231418 *** (0.2159)	5.281513 *** (0.2176)	0.5804531 *** (0.0182)
D_2010-2014	0.5120481 *** (0.0095)	3.751069 *** (0.1519)	3.7787 *** (0.1513)	0.5099568 *** (0.0096)
R^2	0.6279	0.4528	0.4545	0.6681
Observations	24,380	24,380	24,380	19,801

Significance levels: * = 90%; ** = 95%; *** = 99%; Standard errors in brackets.

Model 1a: Lagged log variables

This model contains (log-transformed)[18] variables for bunker fuel prices and charter rates in specific years. As shown in Table 8, the estimated coefficients of the model with lagged log variables are highly significant. As indicated by an R^2 of 0.63, the model has a decent fit.

As it will take some years before the efficiency of new-build ships will react to changes in fuel prices (and other economic variables), we included lags for the effect of fuel prices and charter rates. We tested with different time lags in order to accommodate for these possible delayed effects, up to twelve years. Most (combinations of) lags gave significant outcomes for fuel prices and charter rates, as well as most of the other variables in the model. Ultimately, we chose a 6-year lag for fuel prices and 2-year lag for charter rates. We selected these lags by optimising the model on the significance of the coefficients (especially fuel price), the overall fit of the model, and level of multicollinearity.

Textbox 2 - Interpretation selected lags for fuel prices and charter rates

Note that there is a difference in selected lags for the fuel price and charter rate variables. As we used charter rates as a proxy for the economic conjuncture, an explanation for this could be that for the business case ship owners look at the economic market conditions (material costs, interest rates, etc.) on a shorter term than fuel prices.

Note, moreover, that the period between ordering a ship (and thus, making the investment decision) and its delivery is typically longer than two years. The fact that a 2-year lag for charter rates is significant and provides a good fit of the model, most likely demonstrates that ship owners include a projection of important economic factors in their investment decisions. As this model only looks at *specific years*, this 2-year should be interpreted as a proxy for longer periods (how Model 2 is modelled), for example, as a midpoint of a 4-year period.

The results suggest that a 1% increase in fuel price in a certain year leads to a 0.26% decrease in EIV (hence, a better efficiency) six years later. Note that we have based our analysis on yearly averages for fuel prices. When inspecting the development of fuel prices over time, the data show a fluctuating, but upward-sloping trend (see Figure 3). Most likely, ship owners do not react to incidental spikes in fuel prices but base their investments on more long-term trends. Therefore, we interpret the yearly fuel prices in our model as a proxy or indicator of a long-term trend.

Looking at the effect of charter rates on the EIV, the model shows that a 1% increase in charter rates leads to a 0.41% decrease in EIV two years later. This indicates that better economic circumstances accommodate investments in more efficient new ships.

Differentiating different ship types, the results indicate that, keeping all other factors constant, tankers and bulk carriers are on average 59 and 72% more efficient than container ships[19], respectively. Moreover, the dummies for the different 5-year periods show that the efficiency of new-build ships in the period 1995 and 2014 was worse (hence, having a higher EIV) compared to the reference period 2015-2024. Although the coefficients show some fluctuations in the efficiency of new-build ships, the results seem to demonstrate the autonomous improvement of the efficiency of new-build ships.

[18] This enables us to interpret the coefficients in this model as relative changes (in %) rather than absolute values.

[19] When using log-transformed variables, the coefficient of dummy variables can be interpreted as % change as follows: $e^{\beta i} - 1 = e^{-0.888} - 1 = -59\%$.

Policy effects (most notably, the introduction of the EEDI efficiency requirements for new-build ships in 2015) potentially also play a role, but it is not possible to isolate this effect quantitatively.

Textbox 3 - Real-world illustration

In 2018 the average EIV of new-build container ships was 10.7. The order for a maritime vessel is typically done a few years before the delivery, say, for example, four years. Under this assumption, a ship owner would have considered the historical fuel prices in its investment decision based on the information available in 2014.

Although ship owners will most likely base their expectation on future fuel prices on historic data observed over several years, in this example, we will follow the design of our model – hence, only considering *specific years*. When inspecting the difference in fuel prices between 2018 (year of delivery) and 2012 (year corresponding to the 6-year lag chosen in our model), we see that prices dropped by 35% ($430 in 2018 vs. $660 in 2012). Now suppose that prices in 2012 would have been at the same level as in 2018, hence being 35% lower. In that case, the ship owner would have considered lower fuel prices in its investment decision and thus would have had lower demands for the technical efficiency of the ship ordered. According to the results of our model and all other factors kept equal, this would have resulted in an EIV that was (on average) -35% * -0.26 = 9% higher (thus, being 9% less efficient). Hence, in that case, the average new-build container ship in 2018 would have had an EIV of 11.7 instead of 10.7.

Model 1b and 1c: Lagged variables and interaction effects

The goal of these models is to study whether there might be a different relationship between bunker fuel prices and the EIV of new-build ships for different ship types (tankers, bulk carriers, container ships), and - similarly – for charter rates and the EIV for different ship types. This model contains non-log-transformed variables[20] for fuel prices and charter rates in specific years. As shown in Table 8, the estimated coefficients of the two models with lagged variables (1b and 1c) are highly significant. As indicated by an R^2 of 0.45, the models have a lower, but decent fit as well. Note that – in contrast to Models 1a and 1d – the coefficients in Models 1b and 1c are in absolute terms due to the non-log-transformed variables.

For the interaction effect between tankers and **fuel prices** (*D_tanker * Fuel price y-6*), the coefficient indicates that for tankers, the effect of the fuel price on the EIV of new-build ships (six years later) is .0199615 units higher compared to container ships (the reference ship type), all other factors kept equal. As the overall fuel price effect is -0.0262092, this means that the price effect for tankers is -0.0062477 (or, 75% lower than container ships). This suggests that the efficiency of tankers is less sensitive to fuel price changes than container ships. Similarly, for bulk carriers, the results indicate that the price effect is close to zero (0.000698, or 97% lower), suggesting that effect of fuel price changes on the EIV of new-build bulk carriers is negligible. This could be explained by the fact that bulk carriers typically sail slower, implying that they need less power (or, P_{MEi}; see Section 3.2.1 for the EIV formula) and thus cannot improve their EIV as easily through reducing the numerator.

[20] Including interaction effects in models with log-transformed variables turned out to increase the multicollinearity within the model to a level that would significantly impact the reliability of the model. Therefore, non-log-transformed variables were used to study the interaction effects.

For the interaction effect between tankers and **charter rates** (*D_tanker * Charter rate y-2*), the coefficient indicates that for tankers, the effect of the charter rate on EIV (two years later) is 0.0002439 units lower compared to container ships. As the overall charter rate effect is -0.0000813[21], this means that the charter rate effect for tankers is -0.0003252 (or, four times as high as for container ships). This suggests that the EIV of tankers is much *more* sensitive to charter rate changes than container ships, meaning that – considering charter rates as an indicator for the economic conjuncture - tankers react more strongly to changes in the economy. An explanation for this could be the relationship between the economic conjuncture and the demand for oil on the one hand, and an increase in the demand for oil leading to a higher demand for tankers on the other hand. For bulk carriers, the results indicate that the effect is -0.0000605 (or 26% lower than for container ships), suggesting that the EIV of new-build bulk carriers is *less* sensitive to charter rate changes than container ships.

Model 1d: *x-year averages*

This models contains (log-transformed) variables of *x*-year averages[22] for bunker fuel prices and charter rates. As shown in Table 8, the estimated coefficients of this model are highly significant, and the model has a good fit (as indicated by the R^2 of 0.67).

For the effect of fuel prices and charter rates, again in order to accommodate possible delayed effects, we tested with different periods *x* over which we calculated the averages. For example, with a 2-year average we compare the EIV of new-build ships with the average fuel price over the last two years (for a 4-year period we compare the EIV of new-build ships with the average fuel price over the last four years, etc.). We tested up to 20-year averages. Again, most (combinations of) x-year averages gave significant outcomes for fuel prices and charter rates, as well as most of the other variables in the model. Ultimately, we chose a 14-year average for fuel prices and a 4-year average for charter rates. We selected these lags by optimising the model on the significance of the coefficients (especially fuel price), the overall fit of the model, and level of multicollinearity.

Textbox 4 - Interpretation of selected lags for fuel prices and charter rates

Note again, as discussed for Model 1a, the differences between these lags. When comparing the lags in Model 1a with the lags in Model 1d, we see that the lags for Model 1a (using variables with fuel prices and charter rates for specific years) are more or less in the middle of the periods over which the averages are optimal (2-year vs. 4-year, 6-year vs. 14-year). This confirms the hypothesis that the coefficients in Model 1a should be interpreted as a proxy or indicator of more long-term trends.

Again, an order for a ship is typically placed several years before the delivery of the ship. One could therefore argue that it would be better to calculate the x-year averages over a period ending at the moment of ordering, say, 4 years before the delivery. When testing with such variables, more multicollinearity occurred in the model. Therefore, ultimately, we used x-year averages calculated over the period ending at the moment the ship was delivered. So, if a ship is delivered in 2024, the average fuel price is calculated over the period 2010-2024. Again, as was argued for charter rates in Model 1a, it is likely that projections of fuel prices and charter rates play a role in investment decisions.

[21] Note that the coefficient for charter rates is much smaller (in absolute terms) as the charter rates used in this model ($/day) are much higher than fuel prices ($/tonne), see Table 18.

[22] I.e. the average over a certain period of time. In this case, for example, a 14-year average for fuel prices means the average over the 14 years before the ship is delivered. So, when a ship is delivered in 2024, the average fuel price is calculated over the period 2010-2024.

The results suggest that a 1% increase of the average fuel price over a 14-year period leads to a 0.60% decrease in EIV at the end of this period. Note that this is significantly higher than the effect of a 1% price increase in a specific year to the EIV six years later (0.26%) that we saw in Model 1a. This is intuitive as a 1% higher fuel price over a 14-year period gives a stronger signal to investors than a 1% higher price in just a specific year.
This intuition was confirmed when testing with different periods for the averages: the longer the period over which the average is calculated, the stronger the effect on the EIV of new-build ships. Also for charter rates we see that the effect is stronger than we saw in Model 1a. A 1% increase of the average charter rate over a 4-year period leads to 0.59% decrease of the EIV (compared to 0.41% in Model 1a). Similar to fuel prices, the longer the period over which the average is calculated, the stronger the effect on the EIV of new-build ships.

For the other variables in the model (dummies for ship types and time effects), we found similar outcomes as in Model 1a.

Textbox 5 - Real-world illustration

In 2018 the average EIV of new-build container ships was 10.7. The order for a maritime vessel is typically done a few years before the delivery, say, for example, four years. Under this assumption, a ship owner would have considered the historical fuel prices in its investment decision based on the information available in 2014.

As ship owners will most likely base their expectation on future fuel prices on historic data observed over several years, this model (1d) provides a better representation of the reality than Model 1a, 1b, and 1c.
Now suppose that the average fuel price of the fourteen years (corresponding to the 14-year average chosen in our model) proceeding 2018 (year of delivery) would have been, say, 35% lower than they actually were.
In that case, the ship owner would have considered lower fuel prices in its investment decision and thus would have had lower demands for the technical efficiency of the ship ordered. According to the results of our model and all other factors kept equal, this would have resulted in an EIV that was (on average) -35% * -0.60 = 21% higher (thus, being 21% less efficient). Hence, in that case, the average new-build container ship in 2018 would have had an EIV of 12.9 instead of 10.7.

Relationship between fuel prices and EIV efficiency in 2015-2024

Over the last decade, several policy instruments have been implemented by the IMO and the EU that may affect the energy efficiency of maritime vessels (see Section 1.1 for an overview). One could argue that the implementation of these policies has had an impact on the relationship between fuel prices and the EIV efficiency of new-build ships. Therefore, we carried out two analyses to study whether such a difference in relationship is observable in the data.

Approach 1: Interaction effects

We studied the interaction effects between fuel prices and several dummy variables covering this period (specifically, dummies for the periods 2015-2019, 2020-2024, and 2015-2024) through a modification of Model 1b and 1c. The results provide some evidence that the relationship between fuel prices and EIV efficiency is less strong, but as all models that we tested show signs of high multicollinearity, the outcomes are unreliable. The high level of multicollinearity can most likely be explained by the fact that there is a high correlation between fuel prices and these dummy variables. We also tested with dummy variables for periods before 2015, providing unreliable results as well.

Approach 2: Separate regressions

As an alternative, we ran two separate regressions (modifications of Model 1a): one only including data up to 2015 and the other only including data starting from 2015. The results do show a difference in the coefficients for Log(Fuel price y-6): -0.29 (p-value: 0.000) for observations before 2015 and -0.15 (p-value: 0.000) for observations starting from 2015. Hence, this suggests that the relationship between fuel prices and the EIV is in fact less strong (about 50%) after 2015. As the two regressions are based on two different samples, we should be cautious with the interpretation of the *exact difference* between the outcomes of the two models. However, we view these results as an indication that the relationship between fuel prices and the EIV efficiency of new-build ships is in fact less strong after 2015, the order of magnitude being around 50%.

5.2.3 Model 1.2 (sensitivity analysis)

As a robustness test for the results of Model 1.1, we studied with Model 1.2 the relationship between yearly bunker fuel prices and the technical efficiency of new-build ships as measured by the EEDI between 2010 and 2024. For this purpose, we present the results of two models, equivalent to Models 1.1a and 1.1.d:
- **Model 1.2a**: (log) lagged variables. Similar to Model 1.1a, this model accounts for a delayed effect of fuel prices and charter rates on the EEDI efficiency of new-build ships, where this model considers fuel prices and charter rates in *a specific year*.
- **Model 1.2b**: (log) x-year average variables. Similar to Model 1.1d, this model accounts for a delayed effect of average fuel prices and charter rates *over a multi-year period* on the EEDI efficiency of new-build ships.

Table 9 presents the results of Models 1.2a and 1.2b, where the results of Model 1.1 are added as reference. Compared to Model 1.1, we used the following new variables:
- *D_Phase 0*: dummy indicating the ship fell under Phase 0 of the EEDI;
- *D_Phase 1*: dummy indicating the ship fell under Phase 1 of the EEDI;
- *D_Phase 2*: dummy indicating the ship fell under Phase 2 of the EEDI;
- *D_Phase 3*: dummy indicating the ship fell under Phase 3 of the EEDI.

We have chosen the *non-mandatory* period before the period with *mandatory* EEDI reduction targets (under Phase 0-3) as reference. This means that the coefficients of the dummies per phase should be interpreted as compared to ships in the non-mandatory phase. Note that these dummy variables will represent effects of the EEDI policy as well as time-effects (such as autonomous improvement of the technical efficiency of new-build ships).

Table 9 - Results OLS regressions Model 1.2 (EEDI of new-build ships); results Model 1.1 added as reference

	1.2a: log lagged variables	1.1a: log lagged variables	1.2b: log x-year average variables	1.1d: log x-year average variables
Dependent variable:	Log(EEDI)	Log(EIV)	Log(EEDI)	Log(EIV)
Constant	8.235 *** (0.162)	8.057 *** (0.103)	14.358 *** (0.531)	11.663 *** (0.168)
Log(Fuel price y-6)	-0.062 *** (0.017)	-0.264 *** (0.012)		
Log(Charter rate y-2)		-0.414 *** (0.006)		
Log(Charter rate y-4)	-0.547 *** (0.012)			

	1.2a: log lagged variables	1.1a: log lagged variables	1.2b: log x-year average variables	1.1d: log x-year average variables
Log(Fuel price 10-year)			-0.676 *** (0.082)	
Log(Fuel price 14-year)				-0.602 *** (0.024)
Log(Charter rate 4-year)				-0.593 *** (0.007)
Log(Charter rate 6-year)			-0.811 *** (0.013)	
D_tanker	-0.697 *** (0.015)	-0.888 *** (0.008)	-0.775 *** (0.013)	-0.814 *** (0.008)
D_bulk carrier	-1.156 *** (0.013)	-1.291 *** (0.008)	-1.312 *** (0.012)	-1.167 *** (0.008)
D_Phase 0	-0.239 *** (0.021)		-0.201 *** (0.019)	
D_Phase 1	-0.379 *** (0.021)		-0.348 *** (0.020)	
D_Phase 2	-0.420 *** (0.025)		-0.311 *** (0.027)	
D_Phase 3	-0.473 *** (0.066)		-0.235 *** (0.063)	
D_1995-1999		0.387 *** (0.019)		
D_2000-2004		0.198 *** (0.020)		0.110 *** (0.027)
D_2005-2009		0.600 *** (0.015)		0.580 *** (0.018)
D_2010-2014		0.512 *** (0.010)		0.510 *** (0.010)
R^2	0.550	0.628	0.621	0.668
Observations	7,992	24,380	7,992	19,801

Significance levels: * = 90%; ** = 95%; *** = 99%; Standard errors in brackets.

Model 1.2a: Lagged log variables

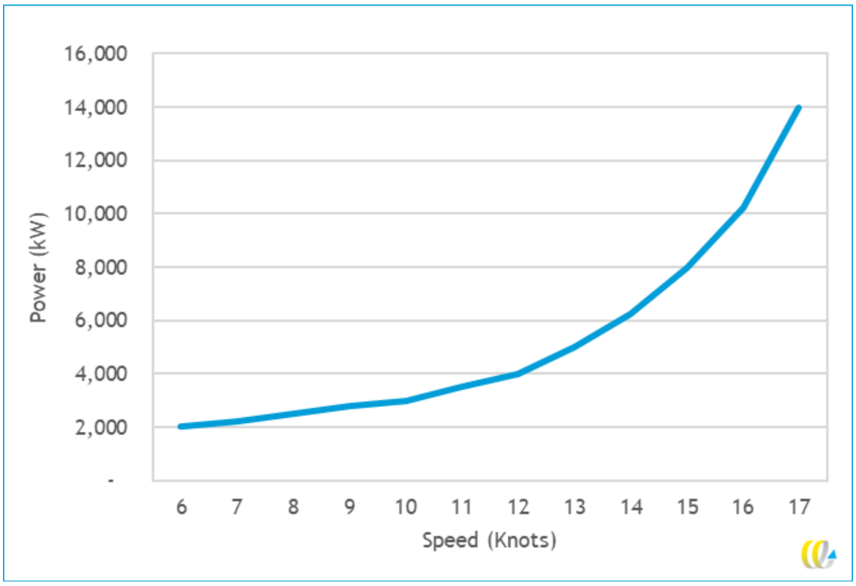
Table 9 shows relatively similar outcomes for Models 1.1 and 1.2. Although the samples of both models are different (1990-2024 vs 2010-2024) and the model contains some different variables (EIV vs EEID and time dummies vs dummies for the EEDI phases), the order of magnitude of the coefficients of most variables are very similar. This provides evidence for the robustness of the results of Model 1.1.

The main difference between the outcomes of both models is the magnitude of the estimated effect of fuel prices on technical energy efficiency of new-build ships. Model 1.2a finds a weaker impact of fuel prices on the technical efficiency. We see two main explanations for the different sizes of these coefficients. First of all, as discussed in the previous section, it is likely that the implementation of policy instruments by the IMO and the EU has had an effect on the relationship between fuel prices and the technical efficiency of new-build ships. Second, the technical energy efficiency is measured differently in both models: in Model 1.1 the EIV is used, while Model 1.2 uses the EEDI.

Differences in the design of both indicators may affect the relationship between fuel prices and technical energy efficiency found by both models. For example, when a ship owner decides to lower the engine power of a new ship in order to reduce fuel costs, this has a larger impact on the EIV than on the EEDI (as is explained in the text box below). This may be an explanation why the EIV seems to be more sensitive to changes in fuel prices.

Textbox 6 - Impact of engine power on the EIV and EEDI

An option to increase the technical energy efficiency of new-build vessels is to lower the engine power. As the engine power installed is the main parameter in the numerator of both the EIV and EEDI, both indicators are directly affected by this technical measure (to the same extent). Changes in the engine power installed also have an impact on the reference speed of the vessel, which is another parameter used in the definition of both the EIV and EEDI. However, both indicators differ in the way the reference speed is defined. Whereas the EIV data uses the speed at 100% MCR[23], the EEDI uses speed measured at 75% MCR. Due to the relation between engine power and vessel speed (i.e. the engine power is expected to follow the cube of speed), vessel speed measured at 75% MCR is more volatile to changes in engine power than vessel speed measured at 100% MCR. This is illustrated by the figure below, which shows a design speed curve for a hypothetical vessel with 14,000 kW of engine power. The speed is 17 knots at 100% MCR and about 16 knots at 75% MCR. A reduction in engine power to 10.000 kW would reduce speed at 100% MCR to 16 knots (a reduction of 6%) and for 75% MCR to about 14.5 knots (a reduction of 9%).



Because of the differences on how vessel speed is considered by the EIV and EEDI, adaptations of the engine power installed will differently affect the EIV and EEDI. As mentioned above, the impact on the reference vessel speed will be larger for the EEDI than for the EIV. As the reference speed is included in the denominator of both the EIV and EEDI (and because the nominator of both indicators will be affected in the same way by adapting the engine power installed), this means that the EEDI will be less subject to changes in engine power.

As the results show, also the optimal lags for fuel prices and charter rates are very similar between the two models. The lag chosen for fuel prices is the same for both models, indicating that a 6-year lag provides a good estimation of the delayed effect in this model. The lag for charter rates in Model 1.2 is four years instead of two years. This difference can

[23] Due to historical data availability, the EIV generally considers design speed.

be explained by the different samples used in both models. Finally, similar to Model 1.1, also other lags that we tested for with Model 1.2 provided significant results.
The estimated effect for the different EEDI policy phases (as captured by dummy variables *D_Phase 0*, *D_Phase 1*, *D_Phase 2*, *D_Phase 3*), show that with each phase the technical efficiency of new-build ships has improved. It is likely that part of these effects is attributable to the policy interventions. However, note again that these dummy variables contain potential time effects (e.g. autonomous improvements in the technical efficiency).

Model 1.2b: x-year averages

As for the results of Model 1.2a, the outcomes of Model 1.2b show a lot of similarities with its related model, in this case Model 1.1d. Whereas Model 1.2a suggests that the effect of fuel prices on the EEDI is smaller than on the EIV of new built ships, the results of Model 1.2b indicate the opposite. However, the difference between the coefficients is relatively small: for Model 1.2b the coefficient is -0.676 and for Model 1.1d the coefficient is -0.602 (the difference being 12%). Note that the difference between Model 1.2a and Model 1.1a (-0.062 vs -0.264) was much larger (76%). The differences between Model 1.2a and 1.1d could be explained by the different sample used, the different periods of which the average is calculated, and the different variables used in both models. In contrast to the findings for Model 1.2a, the dummy variables related to the different EEDI phases show a less clear pattern.

Relationship between fuel prices and EEDI efficiency between 2010-2024

As was discussed in the previous sections, the results of Models 1.2a and 1.2b show some signs of higher technical efficiency of new-build ships due to stricter EEDI obligations (especially for Model 1.2a), but this potential policy effect could not be isolated from other time-effects. In order to gain more insight in the relationship between fuel prices and the EEDI efficiency, we carried out several analyses studying possible interaction effects between fuel prices and the dummies for the different phases. This did not provide any significant and/or reliable outcomes, most likely due to the sample size.

5.2.4 Illustrative application of the findings: impact of EU ETS and FuelEU Maritime on technical energy efficiency of new-build ships

The findings of the econometric model show a historical relationship between fuel prices and technical energy efficiency of vessels. Such a relationship is relevant for current and upcoming policies, such as EU ETS and FuelEU Maritime, which (indirectly) affect fuel prices. In this section, we discuss the possible implications of increased fuel prices due to EU ETS and FuelEU Maritime on the technical efficiency of new vessels, using the results of the econometric analyses discussed earlier.

The EU ETS and FuelEU Maritime both increase fuel prices. The EU ETS provides a carbon price while FuelEU Maritime prescribes the use of minimum shares of more expensive renewable fuels. Table 10 provides an overview of the FuelEU Maritime reference value (i.e. comparable to the average WTW CO_2-eq intensity of fuel and gas oils) and the reduction targets. These reduction targets can be achieved by using fuels with lower carbon content such as LNG[24], biofuels[25] and e-fuels.[26] The highest reduction targets can only be achieved by using advanced biofuels and/or e-fuels.

Table 10 - FuelEU Maritime limit values

Reference (WTW g CO_2-eq. per MJ fuel)	2025	2030	2035	2040	2045	2050
91.16	-2%	-6%	-14.5%	-31%	-62	-80%

Source: EU (2023).

For our assessment, we defined a reference scenario for which we assume no implementation of the EU ETS and FuelEU Maritime for maritime shipping. In this scenario, we assume (for simplicity reasons) that only (very low sulphur) fuel oil (VLSFO) is used by the maritime sector. Based on CE Delft (2023), we also defined a policy scenario for the case where the EU ETS and FuelEU Maritime are implemented for the maritime sector. The resulting fuel shares in the years up to 2040 are shown in Table 11, showing increasing shares of biofuels and e-fuels.

Table 11 - Fuel shares in various years

Scenario	Fuel type	2025	2030	2035	2040
Reference scenario	VLSFO	100%	100%	100%	100%
Policy scenario	VLSFO	96%	91%	82%	63%
	Biodiesel	4%	7%	13%	25%
	e-fuel	0%	2%	5%	12%

Fuel price projections for both the reference as policy scenario are shown by Table 12. In the reference scenario, the fuel prices are rather stable over the years. In the policy scenario, on the other hand, the weighted average fuel price shows a significant increase over time. First, this can be explained by the inclusion of maritime shipping in the EU ETS, as the ETS price will be incorporated into the fuel prices.[27] Secondly, the increased shares of biodiesel and e-fuels in the fuel mix due to FuelEU Maritime leads to a rising weighted average fuel price.

Table 12 - Fuel prices (€/MJ)

Scenario	Fuel type	2025	2030	2035	2040
Reference scenario	VLSFO	12	11	10	10
Policy scenario	VLSFO	19	21	23	25
	Biodiesel	31	37	43	50
	e-fuel	62	58	56	53
	Weighted average fuel price	20	23	27	34

Source: (Transport & Environment, 2023), adapted by CE Delft.

24 Range of: 76 - 85 g CO_2-eq./MJ.
25 Range of: 15 - 36 g CO_2-eq./MJ.
26 Range of: 1.15 - 17 g CO_2-eq./MJ.
27 The EU ETS prices assumed are: € 97 per tonne CO_2 in 2025; € 129 per tonne CO_2 in 2030; €159 per tonne CO_2 in 2035; and €189 per tonne CO_2 in 2040 (Transport & Environment, 2023).

As shown by Table 12, due to the implementation of the EU ETS and FuelEU Maritime, the average fuel prices for maritime shipping in the EU may increase with 64% in 2025 to 240% in 2040. However, most vessels do not sail in European waters for the entire time, and therefore are subject to a lower cost increase. T&E has monitored global movements for all vessels which visited the EU in 2023 based on AIS data. The findings (see Table 13) show that only a quarter of emissions from bulkers, tankers and containers which visit the EU is being subject to a price increase. Average vessels are thus subject to fuel price increases of 16% in 2025 to 60% in 2040.

Table 13 - Share of emissions falling under EU regulation

	CO_2 emissions falling under EU policy, 50/50 corrected (Mton)	Total CO_2 emissions (Mton)	Ratio
Bulker	9	54	0.17
Tanker	23	83	0.27
Container	23	86	0.27
Total bulker, tanker & container	**55**	**223**	**0.25**
Other	41	103	0.40
Total	**96**	**326**	**0.29**

Source: T&E SEA model

Using the results from Model 1.2a on the econometric analysis of the relationship between historical fuel prices and technical energy efficiency of new ships (EEDI)[28], which shows that a 1% year to year fuel price increase leads to a 0.062% technical efficiency improvement with a 6-year delayed effect, we find an improvement of the technical energy efficiency of new average vessels of 1% in 2031 and 2% in 2041, ceteris paribus. This calculation considers average vessels in the fleet, implying that only 25% of the fuel consumption by these ships are considered to be subject to higher fuel prices due to EU policies. If we consider the specific case of vessels only sailing between EU ports, the implementation of EU ETS and FuelEU Maritime may contribute to an improvement of the technical energy efficiency of newbuilds by 4% in 2031 and 8% in 2041.

As in general vessels have a lifetime over 30 years, the cumulative technical efficiency improvement of the entire fleet is considerably lower than at the level of new vessels.
For the entire fleet visiting EU ports, an improvement of the technical energy efficiency of about 0.03% in 2031 and 0.7% in 2041 compared to 2023 may be expected due to the introduction of the EU ETS or FuelEU Maritime. Particularly the figure for 2041 is very uncertain, as we do not expect a linear relationship for large price increases over such a long period of time. The figure for the shorter term (2030/2035), on the other hand, provides a more reliable first-order estimate of the order of magnitude of technical energy-efficiency improvement due to fuel price increases that may be expected for new maritime vessels.
The scenario analysis mentioned before provides a good example of the way the findings from the empirical analyses presented in the previous sub-sections can be applied.

[28] We choose to apply the results from Model 1.2a here, as the EEDI better reflects the actual technical efficiency of new-build ships.

There are, however, many important caveats, that should be considered when interpreting the results of this illustrative analysis:

- The estimation is based on a historical relationship between fuel prices and technical energy efficiency, estimated for a period where there were little policies in place (before 2015) and a period in which there were more policies in place (after 2015). It is very uncertain if such a relationship applies to a policy rich future. However, as discussed in Section 5.2.2, we did find evidence that the relationship between fuel prices and technical energy efficiency of new-build ships is different before and after 2015 (the effect being order of magnitude 50% lower after 2015). This suggests that the relationship is in fact affected by the implementation of policy instruments such as the EEDI or EU MRV.
- Our econometric analysis is based on data for the global fleet, while the analysis of the impacts of the EU ETS and FuelEU Maritime is only relevant for vessels visiting Europe. It is likely that these vessels differ in age, size and type compared to the global fleet.
- The EU ETS and FuelEU Maritime does not apply to all fuel consumption of vessels. Both schemes only cover 50% of the emissions from voyages starting or ending outside of the EU and 100% of emissions that occur between two EU ports (and when ships are within EU ports). As mentioned before, about 25% of the emissions of vessels visiting EU ports falls under these regulations.
- The expected fuel price increases due to the implementation of FuelEU Maritime and the inclusion of maritime transport in the EU ETS are larger and longer lasting than seen historically. This makes it uncertain how vessel owners will react and to what extent the relationship estimated on historic data is representative for the future as well.
- There is a lot of uncertainty about fuel price projections as well as the development of global policies to improve energy efficiency of maritime shipping.
- The technical efficiency only improves for new-builds. Given average lifetimes of vessels of sometimes over 30 years, the effects on the overall fleet are significantly lower than the effects for new build vessels (see the illustrative calculation above). It is also uncertain to what extent improvements in technical efficiency result in real world savings as this depends on operational circumstances.

5.3 Model 2: Fuel prices and vessel speeds

5.3.1 Main findings

In order to study the relationship between bunker fuel prices and average vessel speed, we have studied different sub-models, which we will discuss in more detail in the next section. The general conclusion to be taken from the analysis across sub-models is that with the given information, we cannot explain much of the variance in vessel speed using the variables included in the models. The overall ‘fit’ of the model (how well the variables explain the vessel speed) is very low across models, with an overall R^2 of less than 0.2 in almost all models. As such, we cannot draw clear conclusions from the models.
Although highly uncertain, in all models we found a small positive effect of the fuel price on the vessel speed. This means that generally, with these data a higher bunker fuel price is associated with a higher vessel speed. This is an unexpected result, as one would generally expect that when fuel prices increase, fuel efficiency would be sought by decreasing speed (and thus saving fuel). This does not seem to be the case from the findings. Here we do have to take into account that the low explanatory power of the models indicates that we have omitted variables. In these variables, there may be factors that influence the effect of fuel prices on speed. Therefore, it is not possible to draw the certain conclusion that there is a positive relationship between fuel prices and average speed.

Moreover, in most models (except when only tankers and bulk carriers are considered) the charter rate is negatively associated with vessel speed, meaning that a lower charter rate is associated with a higher vessel speed. This is also unexpected. As charter rates rise, we would expect that the vessel speed is increased in order to be able to carry out more orders in a shorter amount of time, and thus maximising profits. However, only when we look at bulk carriers and tankers, do we see this positive association between charter rates and vessel speeds.
This means that for bulk carriers and tankers, we have some indication that our hypothesis is true, but for container ships, we do not have evidence to support our hypothesis.

In all models, we take seasonal effects into account by using dummies for the various seasons: spring (March, April, May), summer (June, July, August), and fall (September, October, November), compared to the winter season (December, January, February). Of course, summer and winter are opposite when considering global shipping across the Northern and Southern hemisphere. Therefore, the seasonal effects are at least partly counteracted within the model. Not in all models there are statistically significant dummy variables for the seasonal effects, but in general in (Northern hemisphere) spring and summer season, vessel speeds are higher on average.

5.3.2 Detailed results

In Chapter 4 we outlined the specifics of the second model. In this model, we take the average vessel speed as the dependent variable, and we evaluate the relationship between fuel prices, charter rates and seasonal effects on the average vessel speed. We estimated various models to test the robustness of the effect of fuel prices on vessel speed:

- **Model 2a and 2b**: fixed effects model[29] on all ship types. This model tests the overall effect of fuel prices on vessel speed, regardless of ship type. In Model 2a, ship type dummies are not included. In Model 2b, the main three ship types are included in the model.
- **Model 2c**: fixed effects model on container ships. This model only takes into account the container ships, as their behaviour may differ from tankers and bulk carriers. This model takes into account the effect of fuel prices on vessel speed for container ships only.
- **Model 2d**:fixed effects model on container ships, with lags. This model takes into account that for container ships, the effect of fuel prices (and charter rates) on vessel speed might be delayed by one or more months, by including lags of these variables.
- **Model 2e**: fixed effects model on tankers and bulk carriers. This model only takes into account bulk carriers and tankers, as their behaviour might differ from container ships.
- **Model 2f**: fixed effects model on tankers and bulk carriers, with lags. This model takes into account that the effect of fuel prices and charter rates might be delayed for bulk carriers and tankers, by including lags of these variables.
- **Model 2g and 2h**: fixed effects model on container ships only, with the global (2g) and China-EU (2h) freight rate index instead of average charter rates.

Table 14 shows the estimation results of the various econometric models. In these models, we make use of the average values for the variables vessel speed; fuel price; and charter rate. The data considers the three main ship types (containers, bulk carriers and tankers) and distinguishes between various dwt brackets. As such, for each ship type, we have the

[29] A fixed effects model, in contrast to a random effects model, controls for unchanging unobserved differences between the various objects (ship categories in this case). This way, time-invariant factors are controlled for. In this case, fixed effects is preferred over random effects since it is likely that there are variables not included in the model that differ per ship type and dwt category, such as average weight or engine efficiency.

average vessel speed and charter rate. Fuel prices are the same across ship types. For each variable, we have monthly data. This makes the dataset a panel dataset, with the ship type as identifier, and a time frequency of monthly data. Vessel speed, fuel prices and charter rates are log-transformed in all models. This improves the normal distribution of the variables, producing better results, and allows to interpret the results as relative changes (%).

Table 14 - Results of statistical models with vessel speed as outcome variable

Results	Vessel speed^ (All ship types)		Vessel speed^ (Container ships)		Vessel speed^ (Tankers and Bulk Carriers)		Vessel speed^ (Container ships)	
	Model 2a: Log FE	Model 2b: Log FE	Model 2c: Log FE	Model 2d Log FE	Model 2e: Log FE	Model 2f: Log FE	Model 2g: Log FE	Model 2h: Log FE
Log(Fuel Price)	0.0197 *** (0.00172)	0.0197 *** (0.00173)	0.0333 *** (0.00302)		0.0118 *** (0.00192)		0.0361 *** (0.00345)	0.0365 *** (0.00346)
Log(Charter rate)	-0.0139 *** (0.00117)	-0.0136 *** (0.00118)	-0.0207 *** (0.00148)		0.00619 ** (0.00217)			
Log(Freight rate, global)							-0.0200 *** (0.00280)	
Log(Freight rate, China-EU)								-0.0163 *** (0.00224)
Log(Fuel Price, T-4)				0.0170 *** (0.00275)				
Log(Charter rate, T-4)				-0.0230 *** (0.00135)				
Log(Fuel Price, T-2)						0.00818 *** (0.00183)		
Log(Charter rate, T-2)						0.00800 *** (0.00208)		
Spring (dummy)	0.00670 *** (0.00167)	0.00669 *** (0.00168)	0.00590 * (0.00292)	0.00239 (0.00273)	0.00720*** (0.00188)	0.0117 *** (0.00181)	0.00275 (0.00314)	0.00269 (0.00314)
Summer (dummy)	0.00352 * (0.00170)	0.00351 * (0.00170)	0.00930 ** (0.00297)	0.0106 *** (0.00272)	0.000392 (0.00190)	0.00467 * (0.00183)	0.00576 (0.00318)	0.00571 (0.00318)
Fall (dummy)	-0.000792 (0.00170)	-0.000802 (0.00170)	-0.00247 (0.00296)	0.00141 (0.00272)	0.000351 (0.00190)	0.00441 * (0.00183)	-0.00508 (0.00318)	-0.00542 (0.00318)
Bulk carriers (dummy)		-0.309 *** (0.0175)						
Tanker (dummy)		-0.270 *** (0.0164)						
Constant	2.577 *** (0.0391)	2.747 *** (0.0183)	2.736 *** (0.0211)	2.850 *** (0.0194)	2.317 *** (0.0234)	2.317 *** (0.0225)	2.660 *** (0.0226)	2.636 *** (0.0209)
No. of observations	2,220	2,220	888	864	1,332	1,314	888	888
R^2 - overall	0.0196	0.891	0.00689	0.0172	0.101	0.129	0.0386	0.0391
R^2 - between	0.186	0.924	0.807	0.805	0.502	0.498	–	0.0000
R^2 - within	0.111	0.111	0.251	0.279	0.0495	0.0565	0.134	0.136

Significance levels: * = 90%, ** = 95%, *** = 99%; Standard errors in brackets.

Model 2a and 2b: Fixed effects on all ship types

These models contain all available data in the dataset, for each of the three main vessel types (containers, bulk carriers and tankers). Model 2b includes dummies for these main categories, whereas Model 2a does not. In Model 2a, the overall R^2 is 0.0196, indicating a very poor fit. It means that only about 1.96% of the variance in vessel speed can be explained by the variables we put into the model. Model 2b shows an overall R^2 of 0.891, which is a much better fit (the model explains about 89% of the variance in vessel speed). However, given that the models are mostly similar, this difference can be entirely explained by the fact that most differences come from the distinction between the three main vessel types. This is also indicated by the high R^2-between of 0.924 in Model 2, which indicates that the model explains the differences between groups very well.[30] The model does not necessarily explain the variances in vessel speed over time very well (as indicated by a low R^2-within of 0.111).[31] As such, we can conclude that these models do not explain variance in vessel speed very well.

Nonetheless, both models suggest a positive association of fuel prices with the vessel speed, indicating that a 1% increase in fuel prices is associated with a 0.0197% increase in vessel speed (in both Models 2a and 2b). This result would oppose our hypothesis that increased fuel prices would provide an incentive to create efficiency by reducing vessel speed, such that fuel consumption decreases. It is difficult to tell what the reason for this result is. Practically, it is possible that ships are under contractual obligations and have delivery deadlines, and thus cannot vary their vessel speed too much. In terms of modelling, the low R^2 indicates that there might be other variables influencing the vessel speed, potentially including variables that interact with fuel prices. As our model contains monthly data, one obvious variable that is not included is day-to-day weather conditions. Although we included seasonal effects, they do not account for varying weather conditions that influence speed of specific voyages. Moreover, we only include *average* speeds for large groups of ships. In practice, ships will vary in efficiency, age of the vessel, maintenance, etc. If the composition of the global fleet changes over time in terms of efficiency and other factors, this is not captured in the current model. Finally, contractual obligations may affect the flexibility to change vessel speed significantly and not accounting for this in the model may affect the results significantly.

The charter rates are negatively associated with vessel speed in both Models 2a and 2b. This indicates that when charter rates increase by 1%, vessel speed is expected to decrease by 0.0139 and 0.0136%, respectively. This seems counterintuitive, as one would expect that charterers have an incentive to carry out more orders in the same amount of time by increasing vessel speed, when charter rates increase. However, when a ship increases its speed, it means that the use of fuel exponentially increases (since efficiency decreases significantly at higher speeds). So, the possibilities of increasing speed in response to higher charter rates is limited by the fact that it also increases fuel costs. As such, the effects of fuel price and charter rates might depend on each other, as they both determine the business case for the operation of a ship. This suspicion is supported by a high level of multicollinearity between the two variables.

[30] The R^2-between measures the proportion of variance in the dependent variable that can be explained by the independent variables, when comparing the differences between the groups (the ship types and dwt brackets in this case).

[31] The R^2-within measures the proportion of variance in the dependent variable (vessel speed) that can be explained by the independent variables *within* each group (ship type and dwt-brackets) over time, focusing on changes within the same group.

Seasonal effects are attempted to be captured by isolating the vessel speeds in the various seasons (according to the months in the Northern hemisphere), with winter as a reference. The results show that in spring months, the vessel speed is higher than in the winter season. Moreover, the summer season also presents a higher vessel speed on average. The models do not show a statistically significant difference between vessel speeds in fall or winter season. For the northern hemisphere, this is in line with expectations, as the seas may be calmer in spring and summer season. The effects are (partly) offset by the fact that the opposite is true in the southern hemisphere. The data suggests that the outcome is consistent with the expectations when the majority of journeys occur in the northern hemisphere.

Textbox 7 - Illustrative example of Model 2a

When we take the results of Model 2a, which includes all three ship types and varying dwt classes, the results show a slight positive relationship between fuel prices and average vessel speed. Even though the results must be interpreted with caution, since the model fit is quite poor, we give an example of what the results would mean in a real-world situation.

When the fuel price is at an average of $ 376 per ton, a ship is sailing at 13.10 knots (the average found in our dataset), and we increase the fuel price by 10% to $ 413.6 per ton, according to the model vessel speed should on average increase by 0.197% (ten times the coefficient of 0.0197), i.e. to 13.13 knots. As can be seen, the found effect in the model is very small and hardly significant for the changes in vessel speed. Even though the found effect is statistically significant, very little can be inferred from this in terms of real-world consequences. Therefore, we refrain from putting forward more real-world illustrations from the other estimated models.

Model 2c and 2d: Fixed effects on container ships

In the next two models, we isolate only the observations for container ships. Since container ships and tankers/bulk carriers may differ in terms of contracting and lead times between finishing the contract and the start of the journey, we tested models for these ships separately and included various lags. This means that we looked at fuel prices one or more months before the time in which the ship is deciding the vessel speed. If a model with lags is more significant than a model without lags, it indicates that the vessel speed is decided based on fuel prices and/or charter rates further back in time. In the case of container ships, contracts are usually set up quite far in advance, which means that when rates and deadlines are set, it is not yet known what the fuel prices and charter rates will be at the time of departure. Thus, decisions on contracts can only be made based on fuel price and charter rate information at the time of creating the contract.

In both models, the R^2-between is quite high with 0.807 and 0.805 respectively. This indicates that the models explain the differences between the various dwt-categories of container ships quite well. This follows logically from the fact that we included averages for the time charter rates for each of the dwt classes, and vessel speed also consists of a monthly average per dwt category. As such, this result is not very significant, and the explanatory power of the model over time and overall is more interesting.

In Model 2c, we show the model for container ships only without lagged variables. Again, the overall fit of the model is very poor with an overall R^2 of 0.00689. In terms of sign (positive or negative effect) and statistical significance, the results for container ships are similar to those of the model with all ship types.

There is a small positive relationship between fuel prices and vessel speed, which does not follow logically from our theory that higher prices are followed by lower vessel speed. The negative effect of charter rates is also counterintuitive.

Model 2d shows the results of model tests with lagged variables for fuel prices and charter rates. The best model fit is achieved with lags of four months for both variables. This means that the variance in the vessel speed is best explained when we include the charter rates and fuel prices of four months prior. The signs and magnitude of the effects are not too dissimilar from the model without lags. The magnitude of the effect of fuel prices on vessel speed is 0.0170, meaning that a 1% increase in fuel prices is associated with a 0.017% increase in vessel speed.

Model 2e and 2f: Fixed effects on bulk carriers and tankers

The next two models contain observations for bulk carriers and tankers together. In theory, these two vessel types are generally similar in terms of contracting. Compared to container ships, contracts are written less far in advance. As such, we expect that the model has a better fit with fewer lags than the model with container ships.

Model 2e shows the results for the model without any lags for fuel price or charter rates. In this case, the model fit is still quite poor with an R^2 of 0.101, but better than the model for container ships. In this model, higher fuel prices are also associated with a higher vessel speed. However, in this case charter rates seem to be associated positively with vessel speed rather than negatively, such as in the previous models. This means that for tankers and bulk carriers, a higher charter rate is associated with higher vessel speed, which corresponds to the hypothesis that higher charter rates incentivise a higher vessel speed in order to complete more assignments.

When considering lags in Model 2f, a lag of two months for both fuel prices and charter rates provides the best model fit with an R^2 of 0.129. This means that compared to container ships, the model for tankers and bulk carriers does indeed seem to fit best with shorter lag times, indicating that there might be truth to the expectation that contracts for bulk carriers and tankers are agreed shorter before the voyage. Both fuel prices and charter rates are again positively associated with vessel speed, meaning that an increase in either one is associated with an increase in average vessel speed.

Model 2g and 2h: Fixed effects on container ships with freight rates

In contrast to tankers and bulk carriers, freight rates are a more common currency than charter rates for container vessels. Therefore, we also re-estimate Model 2c on container ships with freight rates instead of charter rates. Overall, freight rates and charter rates are highly correlated (0.82 in this dataset), as both rates respond to supply and demand mechanisms in the shipping market. In Model 2g, we include global freight rates. In Model 2h, we include average freight rates for China-EU.

When we include freight rates instead of charter rates for the model with container ships, we find similar results to Model 2c, although the overall fit of the model is slightly better, with an overall R^2 of 0.0386 and 0.0391 respectively (compared to 0.00689 in Model 2c). Interestingly, the R^2-between drops to zero or disappears altogether in this model. As both the fuel prices and freight rates do not differ between dwt categories, this model contains no differences in observations between the various dwt-categories in the independent variables. As such, no variation across ships can be observed.

Both the effects of fuel prices and freight rates (vs. charter rates) are of similar magnitude and carry the same sign as in Model 2c. Fuel prices are positively associated with average vessel speed in both Models 2g and 2h. This is the same (counterintuitive) result as Model 2c, where charter rates are included. Freight rates are, whether global or for China-EU, negatively associated with average vessel speed, in a similar vein as charter rates are in Model 2c. As such, this model does not immediately add an explanation of the counterintuitive relationship.

6 Conclusions

6.1 The impact of fuel prices on technical energy efficiency of new-build ships

In this study we have empirically studied the impact of fuel prices on the technical energy efficiency of new ships. More specifically, we have assessed the relationship between bunker fuel prices and both the EIV and EEDI efficiency of new-build ships. The EIV is an indicator measuring the technical efficiency of a vessel, *excluding* efficiency improvements of the engine). The EEDI, on the other hand, is a more detailed indicator that does consider efficiency improvements of the engine. Overall, the empirical models estimated show (highly) statistically significant outcomes and a proper fit.

The main findings of the assessments are:
- The econometric analysis provides evidence that higher bunker fuel prices have a negative effect on technical energy efficiency – meaning the technical energy efficiency of new-build ships increases (becomes better). In other words, high fuel prices incentivise ship owners to build more energy efficient vessels. This relationship is different for different ship types: the efficiency of tankers is less sensitive to fuel price changes than container ships, while the price effect is close to zero for bulk carriers.
- The relationship found between fuel prices and technical energy efficiency of new-build ships are largely similar for models using EIV or EEDI as dependent variable. The main difference is that the relationship between the EEDI and fuel prices seems to be less strong than the relationship between the EIV and fuel prices. One possible explanation may be that the relationship between the EEDI and fuel prices is more heavily affected by other EU and IMO policies that have been implemented over the last decade. This is (partly) confirmed by the fact that the relationship between the EIV and fuel prices seems less strong for the period since 2015 (when most other policies are in place) compared to the period before 2015. Also differences in the definition of the EIV and EEDI may affect the findings of the empirical analyses.
- The analyses also show that higher charter rates (used as proxy for economic conjuncture) have a negative effect on the technical energy efficiency – suggesting that better economic circumstances accommodate investments in more efficient new ships. This relationship is also different for different ship types: the EIV of tankers is much *more* sensitive (about four times as sensitive) to charter rate changes than container ships, while the EIV of new-build bulk carriers is slightly *less* sensitive to charter rate changes compared to container ships.
- Both for fuel prices and charter rates it seems that ship owners consider long-term (historic) trends (up to 20 years) as basis for their decisions on the energy efficiency of new-build vessels.
- As mentioned above, we found evidence that the relationship between fuel prices and the EIV efficiency of new-build ships is less strong after 2015, the order of magnitude being around 50% lower. This suggests that the relationship between fuel and EIV is in fact affected by the implementation of other policies, like the EEDI or EU MRV.
- The results of this analysis support findings from the literature, where some (non-empirical) evidence on a relationship between fuel prices and technical energy efficiency of maritime ships is provided. This study is, to our knowledge, the first providing statistical evidence for the relationship between fuel prices and the technical energy efficiency of ships.

6.2 The impact of fuel prices on vessel speeds

In addition to the assessment of the impact of fuel prices on technical energy efficiency of maritime vessels, we have also analysed the impact of fuel prices on operational energy efficiency. More specifically, we have assessed the relationship between bunker fuel prices and the average speed of maritime vessels. The main findings from these assessments are:

- The model fit for all estimated models was very poor. Most likely, relevant explanatory variables could not be accounted for due to data availability (such as weather conditions, contract details, and fleet composition in terms of average vessel age, efficiency, etc.).
- Overall, our assessments show a small positive relationship between fuel prices and vessel speed. This is counterintuitive, no fuel savings seem to follow from increasing fuel prices. But it is difficult to infer these conclusions since there may be omitted variables (given the poor model fit), as discussed earlier.
- Several studies have already studied the effect of fuel prices on sailing speeds. Some of these studies have shown a causal relationship between these two factors (higher fuel prices leading to lower vessel speeds), be it with a poor fit of the model and/or with a different approach; other studies have not found a relationship. Compared to existing studies, on the one hand, we used a longer period of time. On the other hand, we used more aggregated data (vessel type level) compared to other studies, which investigated individual vessels.

6.3 Potential policy effects

The results of the econometric analyses carried out in this study provides no significant evidence that policy measures that (indirectly) increase fuel expenditures will have short-term effect on energy efficiency and hence CO_2 emissions (e.g. by lowering vessel speed). The lack of evidence found does not mean that there could not be such an effect. No indication for such an effect is, however, found in the data assessed.

The study does show that policies could have a positive climate impact in the longer run. We found significant evidence that higher fuel prices can lead to improved technical energy efficiency of new-build ships, implying that policies that lead to higher fuel costs may (on the longer run) result in more energy-efficient vessels to be built.

The findings of the econometric analysis can be used to estimate the order of magnitude of the effect of specific policies on the technical energy efficiency of new-build maritime vessels. In this study, we have illustrated this for the inclusion of maritime shipping in EU ETS and the implementation of FuelEU Maritime. Our illustrative calculations show that the fuel cost increases that are expected due to the implementation of these two policies may result in an improvement of the technical efficiency of new vessels in the period 2030-2035 of roughly 1%. For new vessels only sailing between EU ports, an improvement of roughly 4% is expected. This larger effect is due to the fact that these vessels are subject to the EU regulations for all their fuel consumption, while for the average vessel this is only for 25% of their fuel consumption[32]. As the lifetime of maritime vessels is 30 years or more, the impact of the EU ETS and FuelEU Maritime on the average technical energy efficiency of the fleet is more limited, about 0.03% for the period 2030-2035.

[32] Partly, because for trips between EU and non-EU ports only 50% of the CO_2 emissions and hence fuel consumption are allocated to EU ports. And partly, because many of the vessels also sail between two non-EU ports.

6.4 Recommendations for further research

In terms of the econometric analysis where vessel speed is concerned, interesting avenues would be to consider this model on ship-level, to take more variation between different ships into account. Moreover, ideally this model would be elaborated to more granular data, such that specific weather conditions are included in the model. In this case, only average data per month was available, which takes away much of the variation that exists on a day-to-day real-world basis. Additionally, data on contractual obligations could improve the fit of the econometric model. These kinds of variables that influence day-to-day decisions are currently not included, resulting in a poor fit of the model. If or when more granular data is available, it would be interesting to reconsider the model and add more explanatory power to the analysis.

References

Acik, A., & Baser, S. (2018). The reactions of vessel speeds to bunker price changes in dry bulk market. *Transport & Logistics*.

Adlan, R., Fronnes, G., Jia, H., Lampe, O., & Stradenes, S. (2017). The impact of regional environmental regulations on empirical vessel speeds. *Transportation Research Part D: Tranport and Environment*, 37-49. https://doi.org/http://dx.doi.org/10.1016/j.trd.2017.03.018

Adlan, R., & Jia, H. (2016a). Dynamic speed choice in bulk shipping. *Maritime Economics & Logistics*(2), 253-266. https://doi.org/doi:10.1057/s41278-016-0002-3

Adlan, R., & Jia, H. (2016b). *Vessel Speed Analytics Using Satellite-Based Ship Position Data*.

Adland, R., Alger, H., Banyte, J., & Jia, H. (2017). Does fuel efficiency pay? Empirical evidence from the drybulk timecharter market revisited. *Transportation Research Part A: Policy and Practice*, *95*(January), 1-12.

Ammar, N. (2018). Energy- and cost-efficiency analysis of greenhouse gas emission reduction using slow steaming of ships: case study RO-RO cargo vessel. *Ships and Offshore Structures*. https://doi.org/https://doi.org/10.1080/17445302.2018.1470920

CE Delft. (2011). *Analysis of GHG Marginal Abatement Cost Curves*.

CE Delft. (2015). *Estimated Index Values of New Ships: Analysis of EIVs of Ships That Have Entered The Fleet Since 2009*.

CE Delft. (2016a). *Estimated Index Values of Ships 2009-2015 : Estimated Index Values of Ships 2009-2015*.

CE Delft. (2016b). *Historical Trends in Ship Design Efficiency : The Impact of Hull Form on Efficiency*.

CE Delft. (2017). *Estimated Index Values of Ships 2009-2016 : Analysis of the Design Efficiency of Ships that have Entered the Fleet since 2009*.

CE Delft. (2023). *Fit for 55 and energy efficiency*.

CE Delft, Dallan Maritime University, ClassNK, Purdue University, Krannert School of Management, Fudan University, ICCT, Manchester Metroplitan University, NMRI, UMAS, & Fipe. (2020). *Fourth IMO Greenhouse Gas Study 2020, IMO GHG Study 2020 - Full report and annexes*. https://wwwcdn.imo.org/localresources/en/OurWork/Environment/Documents/Fourth%20IMO%20GHG%20Study%202020%20-%20Full%20report%20and%20annexes.pdf

DNV. (2022). *Decarbonization - Act Now: An accessible pathway for all upstream operators to reduce direct emissions - Technical Paper*.

DNV GL. (2014). *Energy Management Study*.

EC. (2020). *Commission Staff Working Document Full-l report lenght report Accompanying the document Report from the Commission 2019 Annual Report on CO2 emissions from Maritime Transport, C(2020) 3184*. https://ec.europa.eu/clima/sites/clima/files/transport/shipping/docs/swd_2020_82_en.pdf

EU. (2023). *Regulation (EU) 2023/1805 of the European Parliament and of the Council of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (Text with EEA relevance)*. https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=uriserv%3AOJ.L_.2023.234.01.0048.01.ENG&toc=OJ%3AL%3A2023%3A234%3ATOC

IMO. (2014). *Third IMO GHG Study 2014*.

IMO. (2024). *Energy efficiency technologies information*. https://greenvoyage2050.imo.org/energy-efficiency-technologies-information-portal/

Jacks, D., & Stuermer, M. (2021). *DP15956 Dry Bulk Shipping and the Evolution of Maritime Transport Costs, 1850-2020*. https://cepr.org/publications/dp15956

Jonkeren, O., Van Ommeren, J., & Rietveld, P. (2012). Freight Prices, Fuel Prices, and Speed. *Journal of Transport Economics and Policy*, 175-188. http://www.jstor.org/stable/24396361

Lagouvardou, S., Psaraftis, H., & Zis, T. (2022). Impacts of a bunker levy on decarbonizing shipping: A tanker case study. *Transportation Research Part D : Transport and Environment*. https://doi.org/https://doi.org/10.1016/j.trd.2022.103257

Lindstad, H., Sandaas, I., & Stromman, A. (2015). Assessment of cost as a function of abatement options in maritime emission control areas. *Transportation Research Part D : Transport and Environment*. https://doi.org/http://dx.doi.org/10.1016/j.trd.2015.04.018

Longarela-Ares, A., Calbo-Silvosa, A., & Perez-Lopez, J. (2023). Investment preference for either technical or operational energy efciency measures to achieve sustainable maritime shipping. *Environment, Development, Sustainability*.

MARPOL. (ongoing). *MARPOL Annex VI: EEDI & SEEMP*. https://www.marpol-annex-vi.com/eedi-seemp/#:~:text=The%20Ship%20Energy%20Efficiency%20Management%20Plan%20(SEEMP)%20is%20an%20operational,in%20a%20cost%2Deffective%20manner.&text=Guidelines%20for%20calculation%20of%20reference,215(63).

MEPC. (2012). *Guidelines for Calculation of Reference Lines for use with the Energy Efficiency Design Index (EEDI) MEPC 215(63)*.

MEPC. (2018). *MEPC.308(73) - 2018 Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships*. https://www.liscr.com/sites/default/files/liscr_imo_resolutions/MEPC.308%2873%29.pdf

Notteboom, T., & Vernimmen, B. (2009). The effec of high fuel costs on liner service configuration in container shipping. *Journal of Transport Geography*, *2009*(17 (5)), 325-337.

Pierre, C., Francesco, P., & Theo, N. (2019). Towards low carbon global supply chains: A multi-trade analysis of CO2 emission reductions in container shipping. *International journal of production economics*. https://doi.org/https://doi.org/10.1016/j.ijpe.2018.11.016

Rehmatulla, N., Calleya, J., & Smith, T. (2017). The implementation of technical energy efficiency and CO2 emission reduction measures in shipping. *Ocean Engineering*, *139*, 184-197. https://doi.org/https://doi.org/10.1016/j.oceaneng.2017.04.029

Rojon, I., & Smith, T. (2014). *On the attitudes and opportunities of fuel consumption monitoring and measurement within the shipping industry and the identification and validation of energy efficency and performance intervention*.

Transport & Environment. (2023). *Modelling The Impact Of FuelEU Maritime On EU Shipping*.

UMAS. (2021). *Harnessing the EU ETS to reduce international shipping emissions*. https://www.u-mas.co.uk/wp-content/uploads/2021/12/UMAS-2021-Harnessing-the-EU-ETS-to-reduce-international-shipping-emissions.pdf

UMAS. (2023). *How can international shipping align with 1.5ºC - focus on 1.5ºC alignment in 2030*.

Zhang, H., & Zeng, Q. (2015). A study of the relationships between the time charter and spot freight rates. *Applied Economics*, *2015*(9), 955-965. https://doi.org/10.1080/00036846.2014.985371

A Detailed assessment relevant variables

A.1 Introduction

As part of this study, we have carried out a detailed analysis of potential variables to be included in the econometric analyses, including an assessment of the data availability to operationalise the variables. The results of this analysis are presented in this annex.
To structure the annex, we first present our findings for the dependent variables (Annex A.2), followed by the independent variable (Annex A.3) and potential control variables (Annex A.4).

A.2 Dependent variables

Variables covering the energy efficiency of maritime shipping are potential dependent variables in the econometric analyses. Here, we distinguish between variables referring to the overall efficiency of maritime shipping, technical efficiency of vessels or operational efficiency of maritime transport.

A.2.1 Overall energy efficiency

Table 15 presents four different metrics presented by the Fourth IMO GHG study (CE Delft et al., 2020) which can be used to measure the overall carbon efficiency (i.e. considering both technical and operational efficiency) of maritime ships. As discussed in Section 1.2, there is a close relationship between carbon and energy efficiency, particularly as the uptake of renewable fuels for maritime shipping is very limited. Therefore, carbon efficiency metrics are a good proxy for the energy efficiency of maritime ships.

Table 15 - Four types of metrics for carbon efficiency

	EEOI	AER	DIST	Time
Description	CO_2 emissions per actual cargo tonne-miles or passenger miles (sum of the product of payload and the corresponding distance travelled), in gCO_2/tonne/nautical mile.	CO_2 emissions per unit of nominal transport work (product of a ship's capacity and total distance travelled), in gCO_2/dwt/nautical mile.	CO_2 emissions per distance travelled, in $kgCO_2$/nautical mile.	CO_2 emissions per hour underway, in $tonneCO_2$/hour.
Benefits	Complete, as it considers the technical efficiency and operational load factors.	Differences in vessel size are considered.	Easy to understand.	Easy to understand.

	EEOI	AER	DIST	Time
Drawbacks	Data availability is limited as information on transport work is commercially sensitive information for vessel owners.	Actual load factors of vessels are excluded.	Differences in vessel size or load factor not considered.	Differences in vessel size or load factor not considered.

The four metrics differ with respect to the elements affecting energy/carbon efficiency of ships that are included. Except for the EEOI, all metrics have excluded the actual cargo mass from their formulas, which affects the outcomes of the metrics. For example, an increase in payload utilisation of a ship, will cause a deeper draught and, thus, an increase in fuel consumption. For all metrics except EEOI, this will merely lead to a higher value of CO_2 emissions in the numerators of these metrics whilst leaving the denominators unchanged. As a result, an improvement in a ship's payload utilisation will generally lead to an inferior value of these metrics. Also, a reduction in ship speed will result in different improvements of the carbon intensity performance when using different metrics. For example, a 10% lower sailing speed (from 14 knots to 12.5 knots) could lead to a 30% reduction in carbon emissions per hour. Measured in distance the reduction is not 30% but only 22% as less distance is travelled due to the lower sailing speeds. Hence, the same operational measure results in different results for the metrics DIST and Time.
The abovementioned examples illustrate that it is not possible to directly compare the various metrics with each other.

Data availability

The main data sources that provide metrics for overall carbon or energy efficiency are the 4th IMO GHG and the EU MRV.[33] The usability of these data sources is evaluated on the following aspects (see also Table 16):
- **Modelled vs. measured data**. The main difference between both data sources is that the indicator for carbon efficiency from the 4th IMO GHG is modelled, while the EU MRV is based on measured data. Using a modelled indicator would provide a drawback as the indicator for efficiency would be based on variables (for example the distribution of the fleet or EEDI regulations) that, ideally, would also be included in an econometric model. This would result in attempting to explain the behaviour of an indicator with data that have modelled the behaviour of the indicator in the first place. Therefore, from a data quality perspective, the EU MRV data would be preferred.
- **Vessels vs. vessel classes**. The EU MRV provides data for about 5,000 unique vessels, whereas the 4th IMO GHG study provides data for 64 different vessel type and size classes. As more detailed data increases the chance of significant results, based on this aspect, the EU MRV data would be preferred.
- **Time period**. The EU MRV and the 4th IMO GHG study provide data for a period of five years and seven years[34], respectively. As the data from both sources concern yearly data, the period of time is too limited for proper analysis. Dependent on the granularity of the data (i.e. unique vessels or vessel classes) and the amount of observations, a proper econometric analysis would require at least ten to fifteen years of yearly data.

[33] Clarksons does not provide efficiency data directly, but it may be derived for a selection of the fleet.
[34] Using the results from an earlier study (third IMO study (IMO, 2014)) is not possible as no efficiency indicators were calculated.

Therefore, we concluded that based on the evaluated aspects we mentioned before, the amount of data points of the current variables of overall carbon/energy efficiency in shipping were too limited to carry out a proper econometric analysis.

Table 16 - Data sources for overall carbon and energy efficiency of vessels

Data source	Description	Granularity
4th IMO study	The Fourth IMO GHG study presents carbon intensity modelled for four metrics: EEOI, AER, DIST and TIME.	– # vessels: 64 classes (13 vessel types with various size classes). – Time period: annually 2012-2018. – Calculation options for differentiating domestic and international traffic: one based on ship size, and one on port calls.
EU MRV	The EU MRV reports annual average CO_2 emissions for several indicators.	– # vessels: ~ about 5,000 recurring vessels across five years. – Time period: annually 2018-2022. – Metrics: per distance, per transport work; time can be derived.

A.2.2 Technical energy efficiency

With respect to technical energy efficiency, we first consider potential metrics that define technical energy efficiency at the level of individual ships. Additionally, we have looked at the uptake of individual energy-efficiency measures.

Technical energy efficiency at the ship-level

Specific metrics that could be used to measure the technical energy efficiency at the ship-level are the Energy Efficiency Design Index (EEDI) and the Estimated Index Value (EIV). As discussed, as of 2013, new ships are required to have an Energy Efficiency Design Index (EEDI) and to prove that the ship is more efficient than a minimum standard. The EEDI is only applicable to new-builds and vessels build before 2013 do not have an EEDI. The EIV is a simplified form of the EEDI. In contrast to the EEDI, the EIV can be calculated based on publicly available data. The EIV was also used to set the EEDI reference lines.

The EIV is given by the following formula (MEPC, 2012):

$$EIV = 3.1144 \cdot \frac{190 \cdot \sum_{i=1}^{NME} P_{MEi} + 215 \cdot P_{AE}}{Capacity \cdot V_{ref}}$$

With

3.1144 = the CO_2 emission factor of fuel (g CO_2/g fuel oil);

190 = the specific fuel consumption of main engines (g/kWh);

215 = the specific fuel consumption of auxiliary engines (g/kWh);

PME(i) = 75% of the total installed main power (MCRME) (kW);

PAE = the auxiliary power calculated according to Sections 2.5.6.1 and 2.5.6.2 of the annex to MEPC.212(63) (kW);

Capacity = 70% of dead weight tonnage (dwt) for container ships and 100% of dwt for other ship types (tonnes);

Vref = speed as indicated in the database (knots).

The formula for the EEDI takes the same approach, dividing technical CO_2 emissions by capacity and speed, but introduces several additional ship specific factors. Foremost, the fuel specific fuel consumption is ship specific and not based on fixed values. Furthermore, there are correction factors for ship specific design elements, capacity limiting factors due to regulations and innovative energy efficiency technologies (MARPOL, ongoing). This allows, for example, ice-classed ships to have larger engines without exceeding EEDI reference lines.

Table 17 describes the benefits and drawbacks of both metrics. The main benefit of EEDI is that it provides a better estimate for technical efficiency of vessels as it uses ship specific fuel consumption factors, and thus includes progression in engine technology.
Also, effects like limitations to carrying capacity due to regulations are corrected for, which theoretically reduces the influence of fleet composition and regulation over time. The EIV considers less vessel specific values but has the great benefit that it can be calculated for existing vessels based on public data. It offers a good indication of technical efficiency excluding engine efficiency. The absence of vessel specific correction factors can have a significant influence at vessel level, but in a larger dataset these will (to some extent) average out for the fleet.

Table 17 - Benefits and drawbacks of technical efficiency metrics

Name	EEDI	EIV
Description	Estimated CO_2 emissions per cargo tonne-miles or passenger miles corrected for ship-specific limiting factors.	Estimated CO_2 emissions per cargo tonne miles or passenger miles.
Benefits	Ship-specific calculated values; includes ship specific fuel consumption.	Differences in vessel size are considered.
Drawbacks	Not available for ships build before 2013.	Does not consider ship type-specific fuel consumption and other vessel characteristics.

Data availability

The EU MRV includes data on EIV and EEDI depending on the vessel type. Furthermore, Clarksons provides information on the designed fuel consumption, cargo capacity and design speed for about 17,000 vessels. These parameters are static over time as they depend on vessel design and not actual performance. (CE Delft, 2015) has calculated EIV values based on these public data from Clarksons for about 30,000 vessels build before 2013. As the EIV does not consider improvements in engine efficiency, the EIV is on average higher than the EEDI. Due to these differences in outcomes, using the EIV and EEDI as equivalents is not possible.

Table 18 - Data sources for other metrics of energy efficiency of vessels

Data source	Description	Granularity
(CE Delft, 2015) (CE Delft, 2016a)	EIV values have been calculated for 30,000 unique vessels build before 2013.	– # vessels: ~ about 35,000 vessels – Time period: not differentiated towards time, but year of built vessels included.

Data source	Description	Granularity
EU MRV	The EU MRV reports technical efficiency of vessels following EIV or EEDI depending on applicability	– # vessels: ~ about 15,000 vessels. – Time period: annually 2018-2022.
Clarksons World Fleet Register	Designed fuel consumption in tonne per day for: – service speed; – trail speed; – design speed; – laden speed; – ballast speed; – eco-speed (average, laden and ballast); – DP mode.	– # vessel types: individual vessel level. – Availability limited (~17,000 vessels). – Time period: not differentiated towards time, but year of built vessels included. – Other: Clarksons fleet register presents more data on vessels including year of build, owner, and speeds.

Technical energy efficiency at the level of individual measures

An alternative way to define the technical energy efficiency of maritime ships is by identifying to what extent specific energy-saving technologies are implemented (at new and/or existing ships). However, as shown by Table 19, the available data on this element is very limited and therefore judged to be insufficient for an econometric analysis.

Table 19 - Data sources for other technical measures

Data source	Description	Granularity
Clarksons research World Fleet Register	Electronic engine uptake	– # vessel types: individual vessel level. Information known only for limited set of vessels (~200 vessels). – Time period: not differentiated towards time, but year of built vessels included. – Other: differentiation to ECO-engine uptake vessel, scrubber (yes/no) and theoretical CII ratings.
Clarksons research World Fleet Register	Energy saving technologies	– # technologies: 7. – # vessels: about 100 unique vessels. – Time period: not differentiated towards time, but year of built vessels included.

A.2.3 Operational energy efficiency

With respect to operational energy efficiency, only data on sailing speeds is available via public sources. This is in line with types of assessments found in the literature (see Section 2.2).

For sailing speeds there are three relevant data sources (see Table 20), all based on measurements from AIS data (on individual vessel level). Clarksons aggregates these data to the level of vessel types and size classes. For the EU MRV, it is aggregated to annual data. As EU MRV data is only available for five years, this leads to a number of observations that is too limited for our econometric analysis. Using AIS data directly provides several challenges, such as missing data and incorrect values, as is mentioned by (Adlan et al., 2017). Consequently, using these data for the empirical analyses within the scope of this study is not feasible. Therefore, we concluded that the Clarksons data on sailing speed is the best source to be used in this study.

As discussed in Section 2.2, Adland et al. (2017) studied the impact of fuel prices on sailing speeds using monthly sailing speed data for a three year period. Therefore, it may be interesting to see if the conclusions they found hold for a longer period. The monthly sailing speed data of Clarksons provide the opportunity to do this. Looking at aggregated data, however, has the disadvantage that voyage-dependent factors such as weather conditions and contractual constraints, which are highly important for individual trips, are not taken into account in the econometric model, negatively affecting the explanatory power of the model. This is assessed in detail in Chapter 5.

Table 20 - Data sources for sailing speeds

Data source	Description	Granularity
Clarksons research shipping intelligence network	Sailing speeds	– # vessel types: 7 vessel categories, 29 size classes. – Time period: monthly starting in January 2012.
EU MRV	Sailing speeds	– # vessels: ~ about 5,000 recurring vessels across five years. – Time period: annually 2018-2022.
AIS	Sailing speeds	– Individual vessel level. – Time period: AIS is monitored from 2002 onwards, although data from main sources (VesselFinder) is only available from 2009 onwards. – Data is measured real-time but can be aggregated to a period of choice.

A.3 Independent variable

The main independent variable is the fuel prices. The main data source of fuel prices is provided by Clarksons, which is also used by most studies in the literature review (see Chapter 2). The data is available for a long period, starting in 1990 with weekly data. The data is available for seven ports including important bunker locations like Rotterdam and Singapore.

Table 21 - Data source fuel prices

Data source	Description	Granularity
Clarksons research shipping intelligence network	Fuel prices	– # fuel types: HFO and MGO have good availability. LNG, MDO less. – Time period: weekly, monthly, quarterly or annually starting in January 1990. – Locations: 7 ports including Rotterdam and Singapore.

A.4 Control variables

A.4.1 Overview of potentially relevant control variables

There are several control variables that are useful to include, though the exact necessity depends on the dependent variable and the conceptual model (see Chapter 4). An overview of potentially relevant control variables is provided by Table 22. Based on Chapter 2, we identified control variables for two types of econometric analyses: one considering sailing speed as dependent variable and one considering technical energy efficiency of the ship as dependent variable.

Table 22 - Overview of potential relevant control variables

Variable	Important for	
	Sailing speed	Technical energy efficiency
Freight rates which are a proxy for vessel demand and supply. Freight rates are provided by Clarksons and are differentiated to vessel types.	Yes. We expect that higher freight rates increase sailing speed (in order to increase transport volumes and thus income).	Yes. We expect that in periods with high freight rate a higher design speed is preferred over technical energy efficiency.
Fleet age and size. This information is available for a long and granular time period.	Yes, differences in fleet composition influence the average sailing speed.	No, vessel details (size, type) will be included but aggregated figures do not seem necessary.
IMO and EU policies on efficiency are an important potential factor affecting fuel efficiency of vessels. In the last decade, mainly the EEDI seems relevant.	Yes, policy measures can influence saling speed and possibly fuel costs.	Yes, measures (EEDI) influence technical energy efficiency and possibly fuel costs.
Changing weather conditions may affect the (operational) energy efficiency of maritime ships. Also average weather conditions in specific regions (Nordic areas) may affect energy efficiency of vessels.	We expect that for aggregated data the effects will average out. A seasonal dummy could be included (assuming that weather conditions are - to some extent - dependent on the season if it increases the model fit.	Vessels regularly sailing in adverse conditions (e.g. ICE classes) could result in vessel designs with lower technical energy efficiency. This can be included by using a dummy variable.
Principal agent issues, where the owner of the vessel is not responsible for fuel cost if the vessel is rented out. As a result, the vessel owner does have less incentive to invest in fuel efficient technologies. This applies mainly to time chartering of vessels, which is more common in certain markets. At individual vessel level this can be controlled for by checking whether the owner and operator are the same, and to what extent the operators are part of a logistical chain.	Very relevant, as contractual obligations determine who is in charge on the (average) vessel speed.	Relevant, as there may be split incentives.
Differences in sailing locations, as freight rates and sailing speeds could differ depending on the locations.	Expected to average out due to the use of aggregated values.	Expected to be of some effect as sailing locations could influence required engine power or hull characteristics.
Specific vessel characteristics (load factors, routing, design speeds, age).	Expected to average out due to the use of aggregated values.	Operational factors are not relevant in design index.

Differences that only refer to time (such as weather, the economy) that apply to all vessel types could be controlled for by using time fixed effects. This means that time is added as a variable, accounting for changes over time that apply to all vessels. This is more difficult for variables that differ between vessel types.

In the remainder of this section, we discuss the various potential control variables in more detail.

A.4.2 Charter rates and freight rates

There are several methods available to measure freight rates or earnings. Which indicator is most relevant depends on the contract form in each shipping market. The most common forms are:
- own ownership;
- time charters (ship is rented for a period of time);
- voyage charters (ship is rented for specific voyage);
- bareboat (ship is rented without crew).

For each contract form there can be various other types of clauses which further determine which costs are borne by the vessel owner and the charterer. In general, the longer a contract duration the higher the amount of costs borne by the charterer. Fuel costs, an important determinant of shipping costs, can be borne by the vessel owner as well as by the charterer. In case the fuel costs are borne by the charterer, the charter rates paid to the vessel owner will be significantly lower. In general, for voyage charters fuel costs are borne by the vessel owner (and hence included in the freight rates), while for time chartering and bareboat these costs are often borne by the charterer. For own ownership the costs are logically born by the owner. Furthermore, sailing speeds and corresponding fuel consumption is often stipulated in the contracts for time chartering[35], and as a result the sailing speed is constant during the contract duration under normal circumstances. The impact of fuel prices on sailing speed will therefore be low (on the short term) for these types of contracts.

The extent to which the various contract forms are used differs between shipping segments as well as over time. Voyage chartering is more suited to volatile flows of goods while time chartering is suited for more long-term flows of goods. In container shipping own ownership and time chartering are the common methods of employments [36], while for dry and liquid bulk voyage and time chartering are most common methods of employments.[37] In terms of rates, spot rates (term for voyage charter rates) are more volatile as there are higher risks for vessel owners.

Data availability

Clarksons research provides data on freight rates and estimated earnings since 1990 (see Table 23). Data on freight rates are collected on a weekly basis from active shipbrokers. Different types of rates are considered, including time charter rates, and spot rates. These rates are based on broker assessments of current market levels, guided by recent or ongoing market fixtures, or best estimates of likely fixing levels where no relevant market fixtures have been concluded. Earnings ($ per day) are estimated based on the revenue (freight rates plus commission of intermediates (brokers)), estimated costs (fuel, port, canal and ETS) and voyage time as denominator. Average earnings for individual shipping sectors (e.g. ‘Very Large Crude Carrier Average Earnings’) are based on an average of earnings on individual routes, selected so as to represent a ‘basket’ of routes

[35] www.handybulk.com/ship-speed-and-consumption-warranty-in-time-charter-party/

[36] www.hellenicshippingnews.com/record-high-container-order-book-of-7-54-million-teu-signals-significant-change/

[37] www.handybulk.com/dry-bulk-chartering/

representative of typical trading activity and the most common/important routes/trade flows within each sector.

For an analysis of the relationship between fuel prices and the technical energy efficiency of new-build vessels, long time-series data on freight rates may be required. As mentioned before, Clarksons presents data since 1990. There are some older data sources available, e.g. hard copy Annual UNCTAD reports, presenting data for the period before 1990. Publicly available annual and consistent timeseries are, however, not available for the period before 1990. An exception is the Baltic Dry index, which presents data starting from 1985. There have been some *modelling* exercises which combine hard-copy and digital data from different time periods to construct a long period timeseries. Most recent of such exercises is by Jacks and Stuermer (2021) who estimate freight rates for dry bulk between 1850 and 2020. However, these data are partly estimated and hence less useful for our assessments.

Table 23 - Data sources for freight rates and charter rates

Data source	Description	Granularity
Clarksons research shipping intelligence network	Freight rates and earnings.	– Markets: Earnings, TimeCharter, TripCharter, Spot, and several indices. – # vessel types: 7 categories including bulk, tanker and container, split into several size classes and type of rates (time charter, Tripcharter and spot). – Time period: weekly, monthly, quarterly or annually starting in January 1990.
Baltic Dry index	The index provides a benchmark for the price of moving the major raw materials by sea.	– Markets: Dry Bulk. – # vessel types: 4 size classes (Capesize, Panamax, Supramax, Handysize). – Time period: daily, for the years 1985-2024.
Jacks and Stuermer (2021)	This study estimates long term dry bulk costs using historical data (tramp shipping rates and UNCTAD).	– Markets: Dry Bulk. – # vessel types: 1 average. – Time period: annually 1850-2020.

The availability of data on freight rates and earnings for the different types of vessels in the Clarksons database is shown by Table 24. *Green* means a good data availability, *yellow* a partial data availability and *red* means no data availability. It is shown that time charter rates have better data availability than earnings and spot rates, especially for container vessels. Only for the largest container vessels no time charter rates are available.

Table 24 - Data availability by vessel type (monthly from 1990 onwards for earnings and charter rates, from 1996 onwards for fleet size and 1993 onwards for age)

Vessel type	Earnings and charter rates			Fleet size	Average age
	Earnings	Time-charter	Spot		
Tankers					
Tanker average					
Handy Tanker					
MR Product Tanker					
LR1 Product Tanker					

LR2 Product Tanker					
Aframax Crude					
Suezmax					
VLCC					
Bulkers					
Bulkcarrier average					
Handysize Bulker					
Handymax Bulker					
Panamax Bulker					
Capesize Bulker					
Containers					
Container ship average					
Feeder Container ship 100-2,999 TEU					
Intermediate Container ship 3,000-5,999 TEU					
Intermediate Container ship 6,000-7,999 TEU					
Neo-Panamax Container ship 8,000-11,999 TEU					
Neo-Panamax Container ship 12,000-16,999 TEU					
Post-Panamax Container ship 17,000+ TEU					
Other					
LNG Carrier (40,000+ cbm)					
Conventional LNG Carrier 60,000+ cbm					
LNG Carrier (Steam Turbine)					
LNG Carrier (Dual Fuel Diesel Electric)					
LNG Carrier (2-Stroke Dual Fuel)					
Handysize LPG 15,000-24,999 cbm					
Midsize LPG 25,000-44,999 cbm					
LGC 45,000-64,999 cbm					
VLGC 65,000+ cbm					
Ro-Ro					
Ro-Ro (3,000+ lane m.)					
Ro-Ro (10,000+ DWT)					
Pure Car Carrier					
Pure Car Carriers (6,000 & Above Vehicles)					

For our assessments we have opted to use time charter rates for four reasons:
1. Unlike trip or spot rates they do not include fuel costs. This ensures that there is less of a relationship with fuel costs, the independent variable.
2. The data is based directly on observations of ship brokers and does involve little or no modelling in contrast to estimated earnings.
3. Time chartering is common practice in all sectors with the exception of (large) container vessels which are under ownership of operators themselves.
4. Data on time charter rates is available for the largest set of ship categories.

As mentioned before, time charter rates are only applied on part of the maritime shipping market. As shown by Zhang and Zeng (2015) spot rates and time charter rates are often related and follow similar patterns. Therefore, we expect that the development in time charter rates provide a good proxy for the balance between demand and supply for market segments where trip charter or spot rates are (mainly) used as well.
Therefore, it seems that applying (the development in) time charter rates could be applied as control variable for all ship categories in the econometric analysis.

A.4.3 Vessel and fleet characteristics

There are several vessel and fleet characteristics that we analysed as they could be relevant for econometric analyses. We have not included these in our model for several reasons. The main ones are:
- **The average age of vessels,** which has impact on the energy efficiency of vessels. The design efficiency of vessel has increased in recent years as shown by (CE Delft, 2016a) which is partly due to a reduction in design speed.
- **The size and composition of the fleet** influences the energy efficiency of shipping as well. Larger vessels have a higher energy efficiency, and certain type of goods are transported more efficiently. In terms of sailing speed larger ships sail faster than smaller ones. Including values for the composition of the fleet may help us to filter out these effects. This is relevant for possible analyses on sailing speeds.

Data availability

As shown by Table 25, the Clarksons database provides relevant data for these characteristics. The data availability per vessel category is shown by Table 24.

Table 25 - Data sources control variables with respect to vessel and fleet characteristics

Data source	Description	Granularity
Clarksons research shipping intelligence network	Vessel average age	– Types: 3 types (bulk, tanker, container) split into several size bins. Also weighted average vessels are available. – Time period: monthly, quarterly or annually starting in January 1993.
Clarksons research shipping intelligence network	Fleet size	– Types: 3 types (bulk, tanker, container) split into several size bins. Also weighted average vessels are available. – Time period: monthly, quarterly or annually starting in January 1996. – Unit: DWT, numbers.

A.4.4 Policy instruments

Over the last decade, several policy instruments have been implemented by the IMO and the EU that may affect the energy efficiency of maritime vessels (see Section 1.1 for an overview). The implementation of these policy instruments can be included as dummy variables in the econometric model(s).

A.4.5 Contractual forms

The contractual form has a large influence on energy efficiency investments of vessel owners. As discussed, in case of time chartering benefits of energy savings will often not go to the vessel owner. This makes vessel owners less willing to invest in energy efficiency measures. This does apply to existing vessels, and likely also to new-build vessels in case the vessel will be rented out.

The contractual form could also affect the average speed of vessels. Sailing speeds are often stipulated in the contracts for time chartering, implying that variance of fuel prices over the contract period is not expected to affect average sailing speed for this type of contracts.

For these reasons, it is preferred to control for the contractual form of the vessel. This can be done by checking if the vessel owner and operator are the same, which is possible using the World Fleet Register of Clarksons research. However, the World Fleet Register focuses on current status of vessels, and historical ownership structures are not documented well. As a result, we deemed that it is not possible to estimate historical ownership and operator structure. This is especially relevant as vessels do change ownership over their lifetime and their contractual form can change. Therefore, we concluded that it is not possible to include contractual forms in our analysis.

Table 26 - Data sources control variables with respect to vessel and fleet characteristics

Data source	Description	Granularity
Clarksons research World Fleet Register	The fleet register provides information for existing vessels including operator and owner names.	– # vessel types: individual vessel level. Information well known. – Time period: only for current fleet. Not differentiated towards time, but year of built vessels included.