



TRA VISIONS 2020

Final Project Template – This template is to be used for submitting the final version of the project. The final deliverable should be submitted by the 31st of October 2019

Idea Number:

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PILLAR / TRANSPORT MODE				
ROAD ☐	RAIL ☐	WATERBORNE ☒	AIRBORNE ☐	CROSS MODAL ☐
Project Re- lated to:	☐ RA1: Climate Change, Mitigation and Resilience ☐ RA2: Digitalisation, Digital Safety and Security ☐ RA3: Automation and Robotisation ☐ RA4: Electrification, Energy and Power Alternatives ☐ RA5: User-focused Mobility services, Servitisation ☐ RA6: Social Change and Quality of Life ☐ RA7: Technology and Engineering ☐ RA8: Planning, Modelling and System Design ☒ RA9: Policy and Regulation, Market Efficiency, Competitiveness ☐ RA10: Transport Safety and Security ☐ RA11: Investments, Finance and Public-Private Partnerships ☐ RA12: Innovation and Human Capital			

Project Title:

Monitoring, Reporting, and Verification of CO₂ Emissions in Shipping: Identification and comparison of available methods



1. Introduction

The climate changes that the world is facing today are already having adverse effects. The primary cause is human activities, such as energy production and agriculture. Greenhouse gas (GHG) emissions will continue to rise to alarming levels unless governments and societies take strong mitigation measures (IPCC, 2014b).

The transport sector is one of the most significant contributors to GHG emissions, accounting for more than a quarter of emissions in 2010, a share projected to nearly double by 2050 (IPCC, 2014a). Road transport is the biggest polluter among all transport modes. However, the other sectors are not innocent. Maritime transport, which has always been seen as environmentally friendly due to its very low carbon intensity (emissions per transport work), had a considerable share of almost 10% of transport-related emissions in 2010 (IPCC, 2014a). Along the same lines, the Third GHG Study of the International Maritime Organisation (IMO) estimated that GHG emissions from international shipping in 2012 accounted for some 2.2% of anthropogenic CO₂ emissions and that such emissions could grow by between 50% and 250% by 2050 (IMO, 2015). For this reason, organisations around the world take initiatives to reduce GHG emissions. At the same time, the international research community investigates and proposes future paths to increase the sustainability of maritime transport by analysing the relevant technical, economic and environmental aspects.

In terms of policy, the monitoring, reporting and verification (MRV) of carbon emissions is generally considered as the first step towards adopting mitigation measures. Two major approaches plus a number of indicators have been proposed for this purpose. The effectiveness of these approaches and indicators in benchmarking ship performance is investigated by this paper through the analysis of voyage-level information on the activity of more than 1,000 dry bulk carriers during 2018. The results indicate that none of the indicators examined is robust enough to be used for this purpose, while the geographic limitations of the EU MRV Regulation introduce a significant bias that prohibits the intended use of the relevant information.

The paper is based on a thesis that the author compiled in the framework of his MSc Degree in Transport and Logistics with the Department of Technology, Management and Economics of the **DELETED DUE TO ANONYMITY CHECK**. The thesis, supervised by Associate Professor Michael Bruhn Barfod and Researcher George Panagakos, covers in addition to dry bulk carriers the segments of tankers, containerhips and Ro-Ro vessels, which, however, are omitted from this paper due to space limitations. The material presented here has also formed the backbone of Panagakos et al. (2019), featuring in the open-access journal Sustainability. The main results of this work were presented at the 6th Intersessional Working Group on GHG meeting at IMO in the autumn 2019.

The motivation for this research is presented in Section 2, while the literature search of Section 3 is focused on the two main alternative monitoring schemes that exist today. Section 4 is devoted to the four most popular operational indicators suggested for benchmarking the energy efficiency of ships. The methodology, data and results of the analysis are presented in Section 5, followed by Section 6, which concludes.

2. Selection of research area

Two major initiatives, one at the regional level in Europe and one at the global level in the framework of IMO exist today. Although both share the aim of improving the carbon footprint of the sector, they differ in the approach they follow and the tools they use.

The EU approach targets the lack of market information on ship efficiency. The so-called MRV Regulation stipulates companies operating ships larger than 5,000 GT that call at EU ports to collect data on fuel consumption, CO₂ emissions and transport work performed as of 1 January 2018 (EU, 2015). The emission reduction mechanism involves the publicising of ship-specific performance indicators (basically in the form of CO₂ per tonne-km) by the European Commission on an annual basis. According to the regulation, the provision of comparable and reliable information on fuel

consumption and energy efficiency is expected to lead to emission reductions of up to 2% compared to business-as-usual, as it could contribute to the removal of market barriers, in particular those related to the lack of information about ship efficiency.

At the global level, the IMO follows a three-step approach that involves: (i) data collection, (ii) data analysis, and (iii) decision-making on what further measures are required. As a first step, the Resolution MEPC.278(70) that entered into force on 1 March 2018, introduced the so-called Data Collection System (DCS) for fuel oil consumption of ships (IMO, 2016a). As of 1 January 2019, all ships of 5,000 GT and above are required to collect consumption data for each type of fuel oil they use. The basic differences to the EU scheme is that now the ship's deadweight is used as a proxy for the rather sensitive transport work figure of the EU, while the aggregated data enter a fuel oil consumption database which is now anonymised.

These developments have triggered a public debate on the approach, indicators and ultimately policy measures to be adopted. Environmentalists, such as the Danish Ecological Council, push for the extension of the MRV system to cover SO_x , NO_x and $\text{PM}_{2.5}$ emissions from ships, for the introduction of a ship labelling system according to environmental performance, and the adoption of speed limits depending on ships' CO_2 emissions (DEC, 2018). On the other hand, shipping interests strongly oppose operational efficiency indexing because external factors such as currents, ocean conditions, weather, and chartering arrangements have a substantial impact on the fuel consumption of ships; even sister ships on similar voyages (ICS, 2018).

The different approaches of the EU and IMO, the multiplicity of indicators proposed for monitoring progress and the conflicting stakeholder interests constitute an open challenge for the research community. The availability of data on fuel consumption, transport work and other variables that shipping companies collate either on a compulsory or a voluntary basis provide a further incentive for research in this field. Denmark, which is home to some of the most progressive shipping companies in the world, and which envisions becoming a global maritime powerhouse by as early as 2025 – with the Det Blå Danmark programme – has a significant role to play in this dialogue. This paper aspires to support this role by expanding the evidence base.

The paper aims to contribute to the policy debate on greening international shipping by analysing available data from a leading Danish shipping company. More specifically, MRV data are combined with ship information at the operation level to: (i) assess the effectiveness of the proposed performance indicators in serving the corresponding policy objectives; and (ii) compare the merits and pitfalls of the approaches that the EU and IMO use in promoting sustainable shipping.

3. Literature Survey

Energy efficiency improvements in the maritime sector require more than just technical solutions. An integrated and coherent approach to ship operations needs key performance indicators (KPIs) for each stakeholder to address their individual performance; as well as KPIs shared across all stakeholders to meet common objectives (Armstrong and Banks, 2015). Monitoring energy consumption is a crucial aspect of best practices in energy management, and a range of options is available to the maritime sector, some more advanced than others (Faber et al., 2009). Acciaro and Wilmsmeier (2015) argue that energy management needs to happen at both strategic and operational levels, and Kitada and Ölçer (2015) call for a new thinking in the sector focusing on energy savings and management.

The following headings focus on the two main international schemes that exist today in relation to CO_2 emission monitoring in the maritime sector.

3.1. The EU MRV Regulation

At the European level, maritime transport remains the only transportation sector not included in the EU's commitment to reduce GHG emissions. The EU has set a target to reduce its GHG emissions by 40% by 2030 compared to 1990 levels (EU, 2014). Hence, the inclusion of the maritime transport sector that has increased emissions by 48% over a seventeen-year period between 1990 and 2007 is of great importance in meeting the 2030 target.

The European Parliament and the Council of the EU emphasised that the best possible option to reduce CO₂ emissions from shipping at EU level is the adoption of the MRV system of CO₂ emissions based on the ship's fuel consumption (EU, 2015). According to this Regulation, as of 1 January 2018, each vessel larger than 5,000 gross tonnage (GT) arriving in or departing from a port of call under the jurisdiction of an EU Member State (plus Iceland and Norway) must collect data on: the ports of departure and arrival, the date and time of departure and arrival, the total amount of fuel consumed by type of fuel, the CO₂ emitted, distance travelled, time spent at sea, cargo carried, and, transport work. Based on these parameters, the following energy efficiency and emissions indicators are calculated and reported on an annual basis:

- Fuel consumption per distance (total annual fuel consumption / total distance travelled);
- Fuel consumption per transport work (total annual fuel consumption / total transport work);
- CO₂ emissions per distance (total annual CO₂ emissions / total distance travelled);
- CO₂ emissions per transport work (total annual CO₂ emissions / total transport work).

The annual reports are submitted to the Commission and the flag State following their approval by the verifiers, which issue compliance documents that need to be kept on board the ships covered by the system. Aiming at addressing the lack of transparency, the Commission publicises the annual values of these indicators, a fact that is expected to help remove the market barriers that prevent the adoption of cost-negative CO₂ reduction measures (Scott et al., 2017). A survey of Norwegian shipowners concluded that the lack of information is a barrier to energy efficiency (Acciaro et al., 2013). It is, thus, argued that the MRV data can serve as a mechanism for the provision of comparable and reliable information on energy efficiency to the relevant markets.

The expected result of the Regulation is a reduction of up to 2% of emissions compared to business-as-usual. In addition to the removal of market barriers, the MRV system would allow companies to identify the potential for fuel economy and enable buyers of transport services to identify the most efficient ships on the market (Maddox Consulting, 2012). Additionally, a robust MRV system is a prerequisite for any market-based measure or efficiency standard whether applied at EU level or globally (EU, 2015).

3.2. The IMO Data Collection System

In 2016, one year after the introduction of the EU MRV Regulation, the IMO adopted its own Data Collection System (DCS) for fuel oil consumption of ships (IMO, 2016a). DCS requires that from the calendar year 2019, all vessels of 5,000 GT and above shall collect fuel consumption data by type of fuel, and that at the end of each calendar year, the collected data should be aggregated and submitted to the IMO. The requirement to report transport work is now replaced by the deadweight (DWT) of the ship as a measure of capacity. Furthermore, no information is publicised. A comparison between the two schemes appears in Table 1.

Furthermore, in April 2018 IMO adopted its initial strategy on reduction of GHG emissions from ships (IMO, 2018). Aiming at phasing out GHG emissions as soon as possible in this century, IMO set the targets of:

- reducing the carbon intensity of ships through strengthening the energy efficiency design requirements for new ships;
- reducing CO₂ emissions per transport work, as an average across international shipping, by at least 40% by 2030, pursuing efforts towards 70% by 2050, compared to 2008;
- reducing the total annual GHG emissions by at least 50% by 2050 compared to 2008.

Note that no indicator is suggested for the second of the above targets as a number of alternative metrics can be used for expressing transport work.

Table 1. Comparison between regulations that promote the reduction of CO₂ emissions

	EU MRV Regulation	IMO DCS
Entry into Force	July 1 st , 2015	March 1 st , 2018
Scope	Ships greater than 5,000 GT conducting to, from, or between an EU port	Ships greater than 5,000 GT conducting an international voyage
First reporting period	January 1 st , 2018 to December 31 st , 2018	January 1 st , 2019 to December 31 st , 2019
Manual	Monitoring Plan following Regulation 2016/1927 (EU, 2016)	SEEMP Part II following MEPC.282(70) (IMO, 2016b)
Compliance	Carry on-board: · Document of Compliance	Carry on-board: · Confirmation of Compliance · Statement of Compliance
Reporting data	· Fuel oil consumption · CO ₂ emitted · Cargo carried · Distance travelled · Transport work · Port of departure and arrival · Time-at-sea and in port	· Fuel oil consumption · DWT · Distance travelled · Hours underway
Reporting format	Standardised format following Regulation 2016/1927 (EU, 2016)	Standardised format following MEPC.282(70) (IMO, 2016b)
Reporting platform	THETIS MRV	IMO GISIS
Reporting deadlines	April 30 th	March 31 st
Verification authority	Third-party independent verifier	Flag State or recognized organization
Publication	Distinctive public database	Anonymous public database

Source: Own compilation based on CSC (2018) and Verifavia Shipping (2019)

4. Indicators for monitoring CO₂ emissions

In the framework of its Ship Energy Efficiency Management Plan (SEEMP), which is mandatory for all existing ships, IMO has proposed using the so-called Energy Efficiency Operational Indicator (EEOI) as a monitoring tool for the CO₂ emissions generated by the ship's operations. Equation (1) presents the definition of the EEOI at voyage level by the ratio of the mass of CO₂ emitted per unit of transport work:

$$EEOI = \frac{\sum_j FC_j \cdot C_{F_j}}{m_{cargo} \cdot D} \quad (1)$$

where FC_j is the mass of consumed fuel type j ; C_{F_j} is the fuel mass to CO₂ mass conversion factor for fuel j ; m_{cargo} is the cargo carried; and D is the distance sailed in nautical miles. Default values of C_{F_j} are provided by the IMO guidelines (IMO, 2009). The cargo carried can be expressed in units such as tonnes, number of passengers, TEUs, lane meters, etc. In order to calculate the average of the EEOI for a period or for a number of voyages, the total mass of CO₂ emissions generated should be divided by the total transport work produced. A more energy-efficient ship has a lower EEOI value, while a larger EEOI figure indicates a less energy-efficient ship. Although introduced by IMO, the EEOI is one of the mandatory indicators stipulated by the EU MRV Regulation.

The m_{cargo} figure of EEOI was considered commercially sensitive by the industry, which expressed serious reservations for this metric. Alternative formulas for the definition of transport work were, thus, needed. In 2014, with document MEPC 67/5/4 (IMO, 2014), Japan proposed the Annual Efficiency Ratio (AER), which is an average value of the EEOI over one calendar-year and with the deadweight tonnage (DWT) replacing the actual cargo volume. AER is defined by Equation (2):

$$AER = \frac{\sum_j FC_j \cdot C_{F_j}}{DWT \cdot D} \quad (2)$$

AER is expressed in the same units as EEOI (gCO₂/ton-mile). However, it greatly underestimates the carbon intensity of the ship since the capacity utilisation of the ship is ignored. Nevertheless, the DCS scheme of the IMO is based on AER.

In 2013, Germany and Japan submitted the document MEPC 66/4/6 (IMO, 2013b) with suggestions of possible metric options. One of them was the Individual Ship Performance Indicator (ISPI) that uses distance as a proxy for transport work:

$$ISPI = \frac{FC \cdot C_F}{D} \quad (3)$$

ISPI is the second mandatory indicator stipulated by the EU MRV Regulation.

In 2013, the USA proposed the DCS for the first time (IMO, 2013a). Due to the lack of standard measurement for cargo transported by ships and concerns about the great effort that might be required to obtain such data, the document IMO (2013a) suggests using operating hours instead of cargo data in the associated metric. Moreover, the adoption of joules of fuel energy rather than tonnes of CO₂ has also been proposed as it provides a uniform and technically accurate method of comparing the use of energy for ships in different types of service and using different fuels. The Energy Efficiency per Service Hour (EESH) is then defined as:

$$EESH = \frac{\text{total fuel consumption}}{\text{total hours of service}} \quad (4)$$

Given that the present analysis concerns only dry bulk carriers and for the sake of compatibility with the other indicators, a modified definition of EESH is used here, where the total mass of CO₂ emitted substitutes for the total fuel consumption:

$$EESH = \frac{\text{mass of CO}_2 \text{ emitted}}{\text{hours of service}} \quad \text{(Error! Reference source not found.)}$$

A number of other indicators have been proposed in relation to either the IMO work or several voluntary schemes that exist today for monitoring ship energy efficiency. Examples include the Fuel Oil Reduction Strategy (IMO, 2013b), the Clean Cargo Working Group (BSR, 2013), and the Clean Shipping Index (CSI, 2018). Nevertheless, only the four indicators mentioned above will be considered in this paper, as they are mandated by the compulsory schemes of the EU and the IMO.

5. The analysis

5.1. Methodology

The methodology selected for studying the effectiveness of the proposed performance indicators and the corresponding approaches is depicted in Figure .

Statistical analysis is used to identify relationships, distributions, trends, and patterns among the indicators and the main factors affecting carbon intensity. The robustness of the indicators is checked by looking at the performance of a single ship at voyage/leg level and the performance of sister ships.

For the purpose of this project, the load factor, defined by Equation (6), is an estimate of a ship's capacity utilisation. It is formulated as the ratio of cargo carried during leg i in comparison to the DWT of the ship. Of course, this is an approximation, as DWT includes also weights such as fuel, drinking water and supplies, ballast water, crew, etc. However, for large ships, the error introduced by the omission of these weights is rather insignificant. So, Equation (6) results in a value between 0 and 1, where 0 refers to a ballast leg, and 1 to a fully loaded.

$$f_{load_i} = \frac{m_{cargo_i}}{DWT} \quad (6)$$

At higher levels (voyage / ship) the load factor is defined as the ratio of the total transport work produced by the participating legs over the DWT of the ship multiplied by the total distance of the corresponding legs.

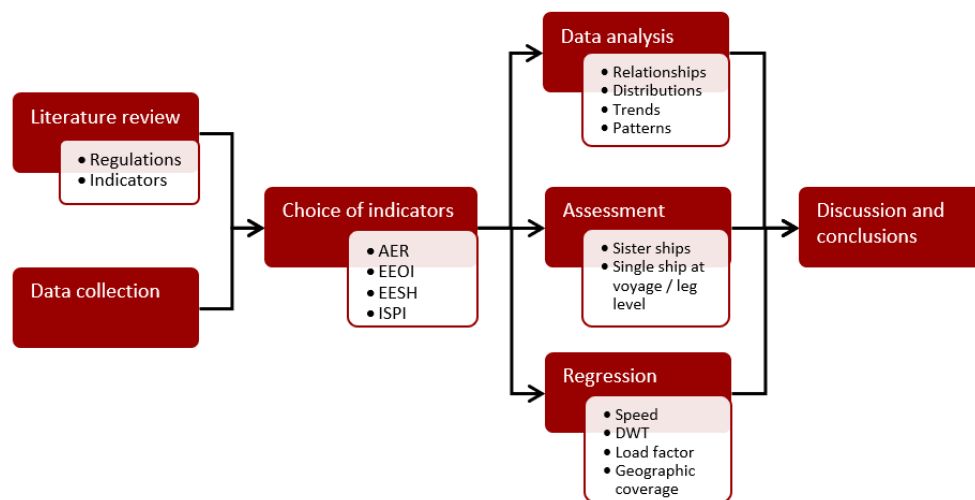


Figure 1. Methodological scheme
Source: Own compilation

5.2. Data description

The data supporting this analysis has been provided by a leading Danish shipowner/operator that specialises in dry and liquid bulk cargoes and which for confidentiality purposes is herewith referred to as Company A. The data set includes all dry bulk carriers that are either owned or chartered by Company A during the period from late 2017 to early 2019. This fleet consists of 1,051 dry bulk carriers, which comprises a considerable sample – around 8% of the world dry bulk carrier fleet by DWT according to UNCTAD (2018). Given that the analysis is restricted to sailings performed in 2018, a number of ships were excluded. This resulted in a fleet of 1,041 ships. They vary greatly in size, with DWT ranging from about 19,000 up to 111,000 tonnes. The average size is about 61,800 tonnes. The composition of the sample fleet by size appears in Table 2.

Table 2. Composition of the sample fleet in terms of size

Size group	DWT range	No of ships	Deadweight (DWT)			
			Min.	Max.	Mean	Std. Dev.
Handysize	10,000≤DWT<40,000	198	18,920	39,880	35,353	254
Handymax	40,000≤DWT<65,000	476	43,176	64,942	58,418	179
Panamax	65,000≤DWT<100,000	365	66,613	95,737	80,311	232
Capesize	DWT≥100,000	2	110,925	110,944	110,935	10
Sample		1,041	18,920	110,944	61,807	16,720

Source: Own compilation

It is worth noting that only about 2% of these ships are owned by Company A, the remaining being chartered in. This fact leads to the identification of an important limitation of the EU MRV Regulation even before analysing the data. According to the EU MRV Regulation, the entity obliged to report emissions is the shipowner. For the vast majority of the Company A fleet, however, the operation of the ships is controlled by the charter (Company A in this case) and not the owner. This results in a major limitation to the effectiveness of publicising the MRV indicators as a means toward enhancing the energy efficiency of the ships since the owner is obliged to report indicators reflecting operating decisions taken by the charters outside its immediate control.

Each entry in the dataset contains the information that pertains to a single leg. The term 'leg' denotes the period between the departure from a port and the departure from the subsequent port. Although this period is defined as 'voyage' in the context of the MRV Regulation, the term 'voyage' is herewith used to denote a set of 'legs,' usually contained in a single charter party. For each leg, the information obtained includes the ship identification (name, IMO number, size group, DWT, and ownership), ports of origin and destination, distance sailed, cargo carried, days at sea and in port, and the fuel consumption at sea and in port (separately for each fuel quality used).

Not all of the observations were complete however. There were cases of missing information such as unspecified ports of origin and destination, unavailable arrival and departure times, and unavailable quantities of cargo carried. In addition, there were observations that contained incompatible information in relation to distances, times, or cargo quantities. These observations were excluded from the estimation of the indicator values. After data cleansing, the dataset consists of 3,540 legs sailed in 2018 by the sample fleet. These 3,540 legs correspond to 1,675 voyages undertaken by 1,005 dry bulk carriers.

Note also that the EEOI of ballast legs cannot be defined since the denominator of Equation (1) becomes zero. Therefore, these cases were considered only when aggregated at voyage or ship level. Furthermore, the EEOI and ISPI of the EU MRV Regulation were calculated for both the EU and global level to investigate the effect of the geographical restrictions imposed by the legislation.

5.3. Indicator values

Following the framework used in Chi et al. (2018), **Error! Reference source not found.** presents the value of EEOI at ship level by size. It shows also the exponential regression curve (in black), as well as the range defined by plus and minus two standard deviations (in blue and red, respectively), which defines the range of the EEOI values at a confidence interval of 95.44%, assuming, of course, that the EEOI follows a normal distribution. What stands out from **Error! Reference source not found.** is the decreasing function of the EEOI with respect to DWT. This trend is due to the economies of scale characterising larger ships, which, when compared to smaller ships, exhibit an increase in fuel consumption that is lower than the corresponding increase in cargo carrying capacity.

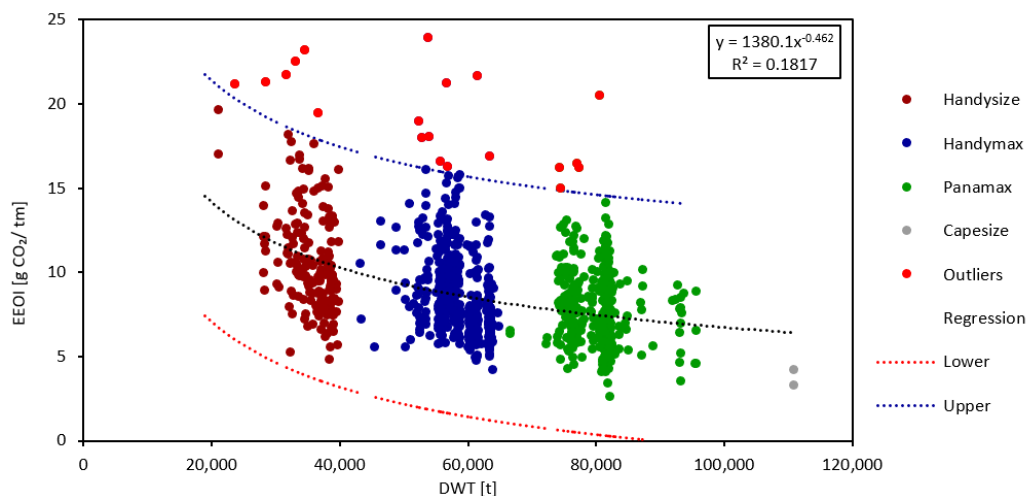


Figure 2. The Energy Efficiency Operational Indicator of the sample fleet by size (2018)
Source: Own compilation

A total number of 26 ships, representing 2.7% of the sample, lie outside this range (they are marked in red). It is interesting to note that all outliers are on the high side of the range. A probable explanation relates to the definition of the indicator and the appearance of the transport work in the denominator. A ship with just a few voyages with very little cargo carried can easily exhibit very high values exceeding the upper limit of $+2\sigma$. As shown in **Error! Reference source not found.**, the range of variation of the EEOI values is quite wide. For example, an 80,000 DWT-tonne ship exhibits values that vary between around 2.6 up to 14.1 gCO₂/tm, indicating that the size of the ship is just one of the variables that affect the EEOI. Smith et al. (2013) investigate the effects of the DWT in the EEOI values for dry bulk carriers. The results presented are similar and the curve observed has the same decreasing tendency on the indicator with ship size.

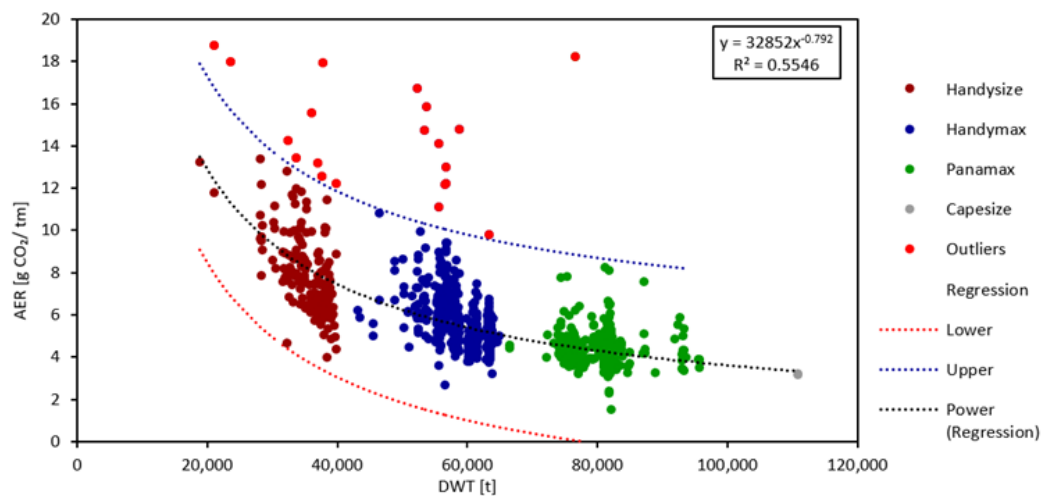


Figure 3. The Annual Efficiency Ratio of the sample fleet by size (2018)
Source: Own compilation

The second indicator analysed is the AER, which is stipulated by the IMO's DCS and uses the DWT as a proxy for the cargo carried. Following the same approach as previously, Figure presents the regression curve of the AER against the DWT of the ship by category. The decreasing function of the EEOI against ship size is maintained for the AER, which now features DWT directly in the denominator. The values of the indicator (expressed in the same units as the EEOI) are now lower, as the actual transport work of the EEOI has been replaced by the maximum possible one, which ignores the capacity utilisation of the ship and produces a significantly underestimated figure of carbon intensity. For the same 80,000 DWT-tonne ship, the AER varies between around 1.5 and 8.2 gCO_2/tm . Furthermore, the variance of the observations is reduced due to the fact that one important variable, the load factor, is not considered anymore. Japan, when proposed the AER (IMO, 2014), argued that the AER is a consistent and effective indicator for measuring energy efficiency based on the robustness of the regression curves when plotted against DWT. When compared to the EEOI curve, the AER does indeed have a better R-squared. However, due to the reasons mentioned above, this statement does not imply that the AER is a better indicator.

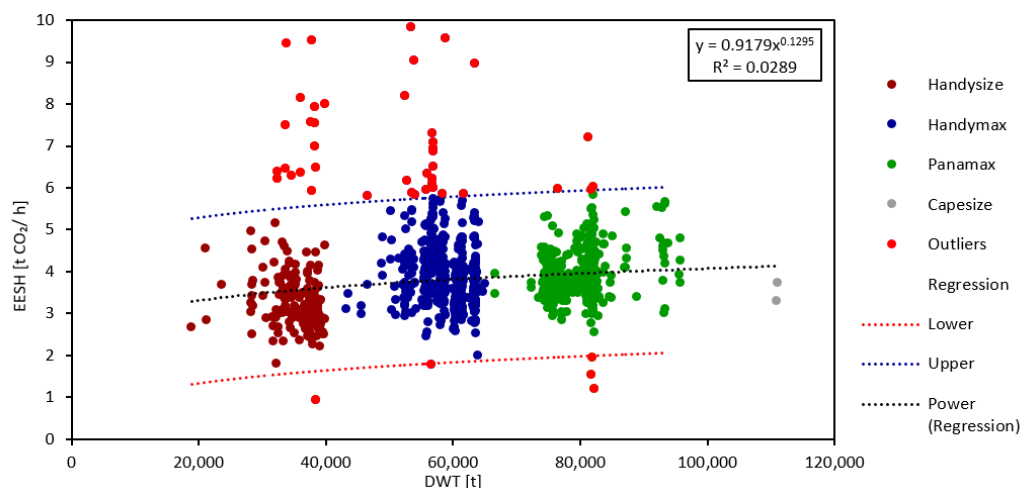


Figure 4. The Energy Efficiency per Service Hour of the sample fleet by size (2018)
Source: Own compilation

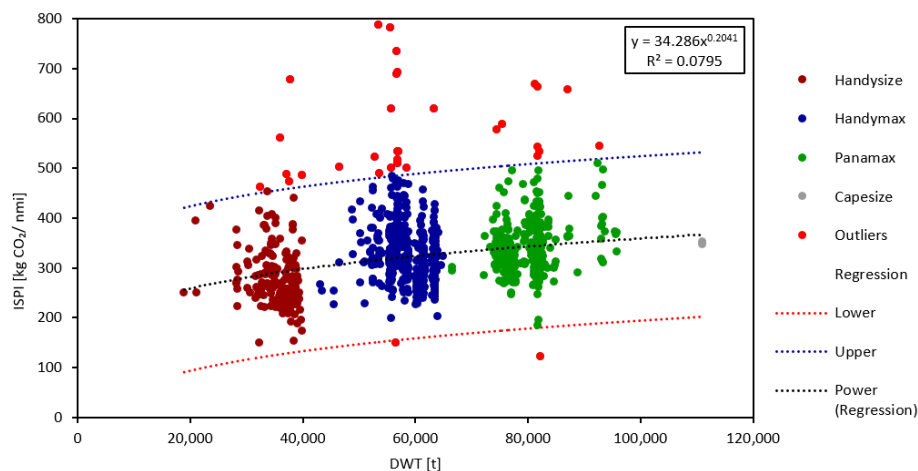


Figure 5. Individual Ship Performance Indicator of the dry bulk fleet by size (2018)
Source: Own compilation

In contrast to the EEOI and the AER, the EESH and the ISPI indicators disregard both the cargo and capacity of the ship. Instead, they use, respectively, the time-at-sea and the distance sailed to approximate transport work. Figure 4 and Figure 5 present the values of these indicators plotted against ship size. Unlike the previous cases, the regression curves now exhibit an upward moving trend due to the fact that, *ceteris paribus*, larger ships emit more than the smaller ones per hour or per mile sailed. There are two points worth to mention here. Firstly, the explanatory power of these models is now very weak, meaning that there are other variables than the size of the ship that have a significant impact on the two indicators. Secondly, although there are now some outliers outside the lower bound, the majority remains above the upper bound. This means that the low load factor, mentioned as a probable explanation of the EEOI and AER outliers, is not alone. There must be other factors behind these high values. Speed is a good candidate.

As expected, the exclusion of the outliers adds power to the exponential regression models that estimate the indicators using the DWT as the sole explanatory variable. The corresponding plots of all four indicators are shown in Figure 6.

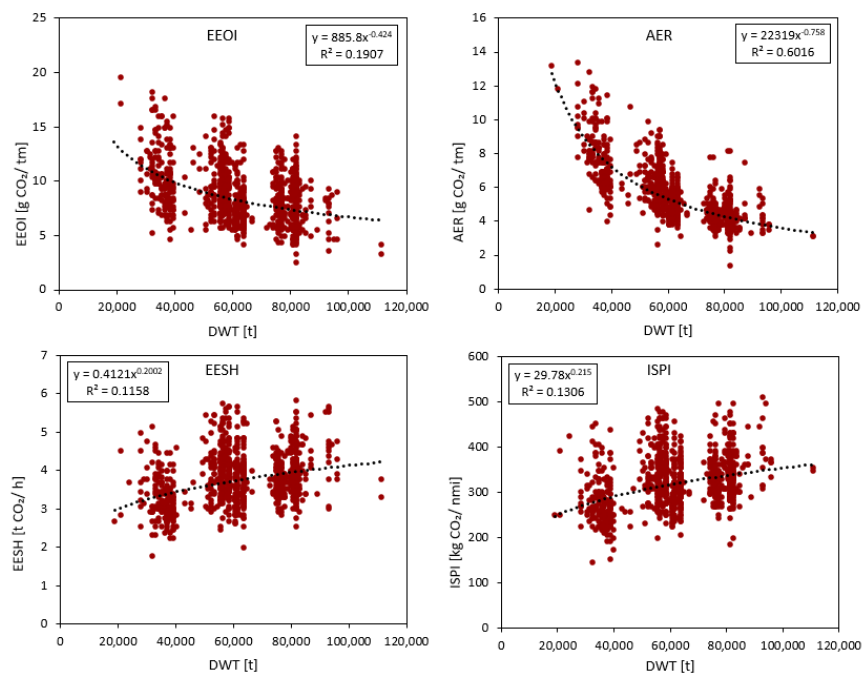


Figure 6. The EEOI, AER, EESH, and ISPI of the sample fleet by size (2018)
Source: Own compilation

5.4. Factors affecting indicator values

Table 2 shows the correlation between the indicators examined and a number of variables that often appear in the bibliography as affecting emissions. The role of the DWT has already been explained in the preceding section. Indicators having transport work in the denominator benefit from the economies of scale offered by larger ships. On the contrary, when the denominator of the indicator formula is independent of the size of the ship, as it is the case with EESH and ISPI, the correlation turns positive as larger ships emit more in absolute terms.

Table 2. The correlation matrix for dry bulk carriers

	<i>DWT</i>	<i>Distance sailed</i>	<i>Time at sea</i>	<i>Cargo carried</i>	<i>Transport work</i>	<i>Load factor</i>	<i>Speed</i>
DWT	1.000						
Distance sailed	0.113 ***	1.000					
Time-at-sea	0.123 ***	0.996 ***	1.000				
Cargo carried	0.490 ***	0.056 *	0.065 **	1.000			
Transport work	0.256 ***	0.940 ***	0.941 ***	0.278 ***	1.000		
Load factor	-0.321 ***	-0.035	-0.034	0.639 ***	0.074 **	1.000	
Speed	-0.187 ***	-0.032	-0.072 **	-0.020	-0.048	0.149 ***	1.000
EEOI	-0.429 ***	-0.209 ***	-0.213 ***	-0.710 ***	-0.373 ***	-0.349 ***	0.207 ***
AER	-0.754 ***	-0.280 ***	-0.284 ***	-0.305 ***	-0.355 ***	0.351 ***	0.134 ***
EESH	0.300 ***	-0.298 ***	-0.309 ***	0.270 ***	-0.199 ***	0.015	0.163 ***
ISPI	0.325 ***	-0.291 ***	-0.282 ***	0.309 ***	-0.187 ***	0.035	-0.066 **

* 0.1 > p-value > 0.05; ** 0.05 > p-value > 0.01; *** p-value < 0.01

Source: Own compilation

All indicators are negatively correlated with the distance sailed. This is not a surprise for the EEOI, AER, and ISPI that feature distance in their denominator. The behaviour of EESH is similar due to the fact that the time-at-sea of its denominator is proportional to the distance sailed. Due to this almost perfect correlation between time-at-sea and distance, all indicators exhibit a statistically significant negative correlation with time-at-sea as well.

The negative correlation between EEOI and cargo carried is reasonable and expected, as the latter appears in the denominator of the former. The negative sign is retained when it comes to AER through the positive correlation of cargo carried with the DWT of the ship. As expected, EESH and ISPI are positively correlated to cargo carried, which increases the emissions of the numerator in absolute terms.

All indicators are negatively related to transport work either directly (EEOI) or indirectly through DWT (AER), time-at-sea (EESH), or distance (ISPI). The situation is different, however, in relation to the load factor. The EEOI exhibits a negative correlation with the load factor as the latter increases the cargo carried of the denominator. On the contrary, the AER is positively correlated, as the load factor increases the emission on the numerator through higher drafts but leave the denominator unaltered. The same reasoning applies for EESH and ISPI, but the values here are not statistically significant.

Theoretically, all indicators should be positively correlated to speed. This is because the emissions of the numerator are proportional to fuel consumption, which for ships such as dry bulk carriers is a cubic function of speed (Psaraftis and Kontovas, 2014). The distance that appears in the denominator, either directly (EEOI, AER, ISPI) or indirectly through time-at-sea (EESH) increases only proportionally to the first power of speed, meaning that the indicators are expected to increase with the second power of speed. The correlation of the EEOI, AER, and EESH have the expected sign. The slightly negative coefficient of ISPI, however, while is still significant at the 95% confidence interval requires further investigation that exceeds the limit of this paper, although the voyage level analysis of Section 5.6 on sister ships exhibits the desired behaviour. Among the variables mentioned above, the load factor and speed seem to be the most interesting ones and they will be monitored in the robustness analysis of the following two sections concerning the performance of a single ship and sister ships, respectively.

5.5. The case study of a single ship

In order to see what hides behind the average indicator values discussed so far, this section presents the results of all voyages performed by a single ship in 2018 on behalf of Company A. The ship examined is a Handysize dry bulk carrier of around 36,800 DWT tonnes, herewith named 'DryBulk_4'. Table 3 presents these voyages in more details. The corresponding EEOI values per voyage are shown in Figure plotted against speed and load factor. The annual EEOI value of the ship is also shown for comparison purposes. A graphical depiction of these voyages appears in Figure 8, where ballast legs are shown in blue and laden ones in red.

Table 3. Set of voyages performed by DryBulk_4 (2018)

Voyage N°	Leg N°	From port	To port	Leg level			Voyage level		
				Distance sailed	Load factor	Speed	Distance sailed	Load factor	Speed
Voyage 1	Leg 1	Port au Prince	Rocky Point	303	-	13.2	4,559	0.87	11.5
	Leg 2	Rocky Point	Dunkirk	4,256	0.94	11.4			
Voyage 2	Leg 1	Dunkirk	Heroya	591	-	6.4	6,708	0.61	10.9
	Leg 2	Heroya	Sluiskil	556	0.29	11.0			
	Leg 3	Sluiskil	Maceio	4,293	0.76	11.4			
	Leg 4	Maceio	Aratu	292	0.63	13.0			
	Leg 5	Aratu	Vitoria	497	0.51	12.8			
	Leg 6	Vitoria	Santos	479	0.42	13.8			
Voyage 3	Leg 1	Santos	Bahia Blanca	1,306	-	12.8	3,750	0.47	11.9
	Leg 2	Bahia Blanca	Suape	2,444	0.71	11.5			
Voyage 4	Leg 1	Suape	Santos	1,240	-	11.5	6,573	0.33	12.2
	Leg 2	Santos	New Orleans	5,333	0.41	12.4			
Voyage 5	Leg 1	New Orleans	Puerto Progreso	558	0.82	17.5	558	0.82	17.5
Voyage 6	Leg 1	Puerto Progreso	Houston	615	-	14.6	7,217	0.86	11.6
	Leg 2	Houston	Lake Charles	171	0.67	25.2			
	Leg 3	Lake Charles	Thessaloniki	6,431	0.95	11.3			

Source: Own compilation

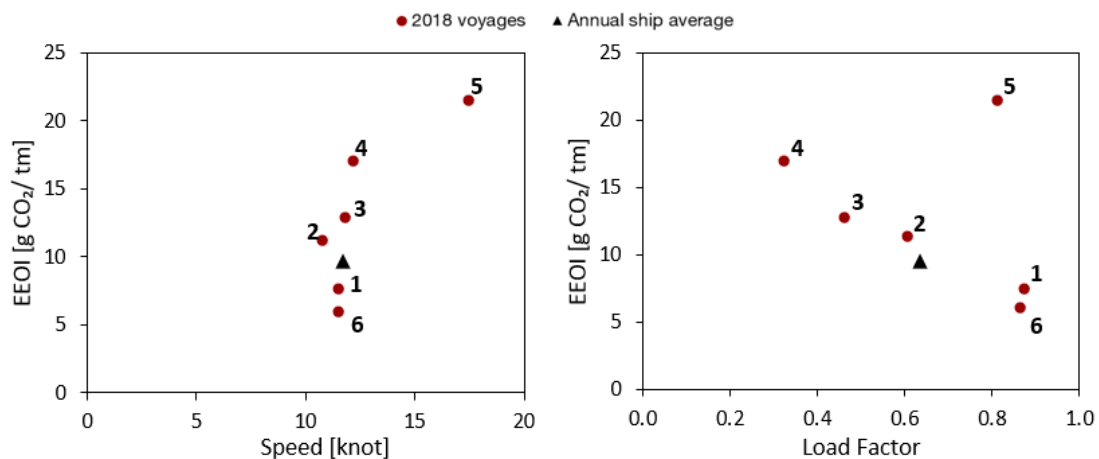


Figure 7. The EEOI for the DryBulk_4's voyages by speed and load factor (2018)

Source: Own compilation

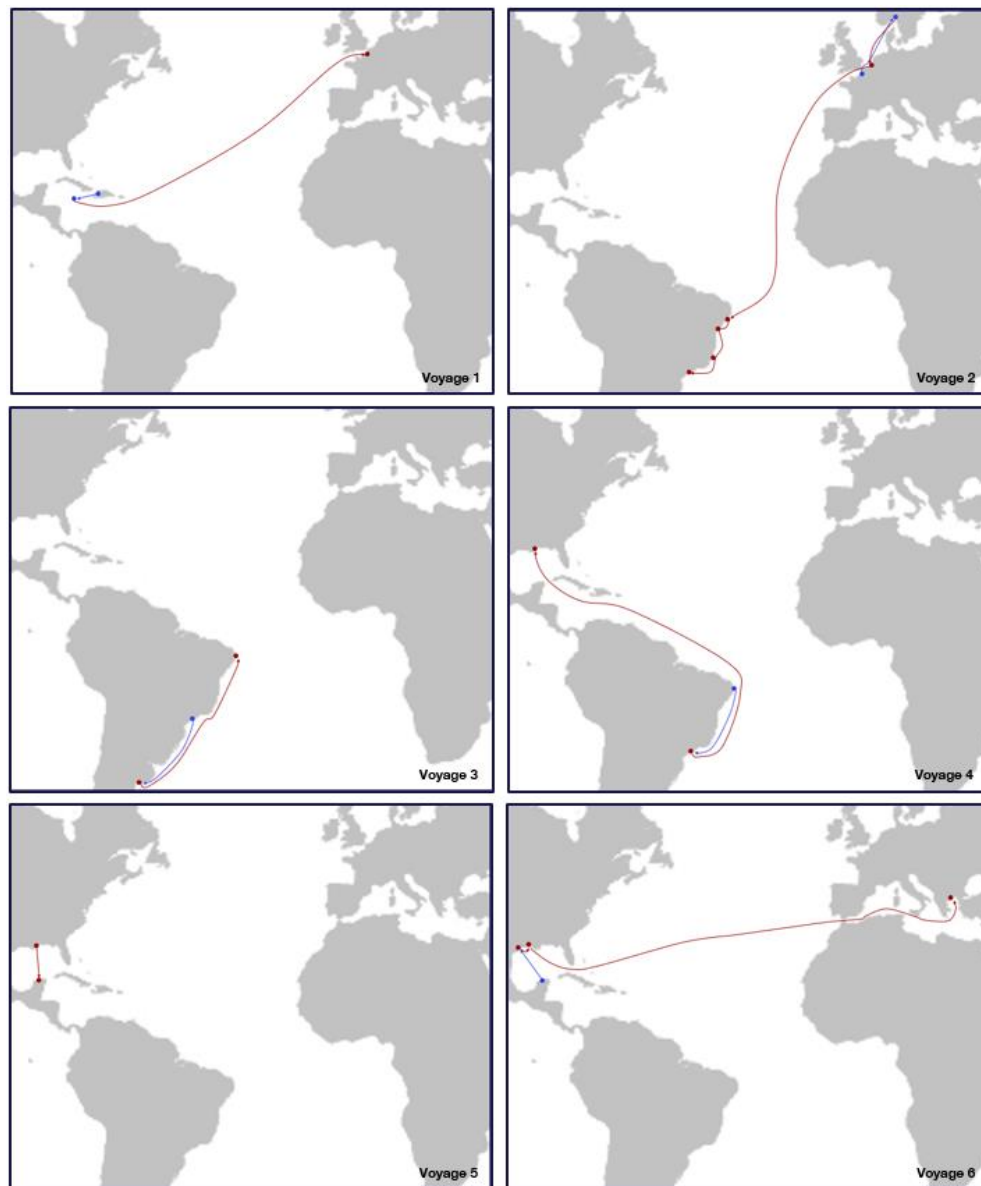


Figure 8. Representation of the voyages performed by DryBulk_4 in 2018
Source: Own compilation

Voyages 1 and 6 display a good utilisation of the ship's capacity and, due to the significantly longer laden than ballast legs, their EEOI values are the two lowest ones (see Figure). Voyages 2, 3, and 4 have similar average speed, but the varying load factors lead to significant differences in the EEOI values. Voyage 5 has the highest EEOI value. There are two reasons for this. Firstly, the speed of this voyage is much higher than that of all the others. Secondly, given that it is a short one-leg voyage, the emissions at berth become a significant share of the total emissions that enter the indicators.

The fact that the EEOI at voyage level ranges from 5.9 to 21.3 gCO₂/tm raises concerns about what value an average figure of 9.7 gCO₂/tm might have in characterising this specific ship. In order to put the numbers in context, they are plotted in Figure against a set of EEOI-speed curves reflecting combinations of the ship's loading condition, the sea state, and the wind direction. They are based on the consumption-speed curves of the main engine after correcting for the fuel consumption of the auxiliary engines and the average share of the time this particular ship spent in port during 2018. Other assumptions used in this calculation include:

- Laden condition: loaded to about 90% of the scantling draft;
- Ballast condition: sufficient ballast to ensure safe navigation at all weather conditions;
- Light ballast condition: only valid for calm seas;
- Calm seas: waves high of 0.3 m and wind speed of BF3;
- Moderate seas: waves high of 1.2 m and wind speed of BF5.

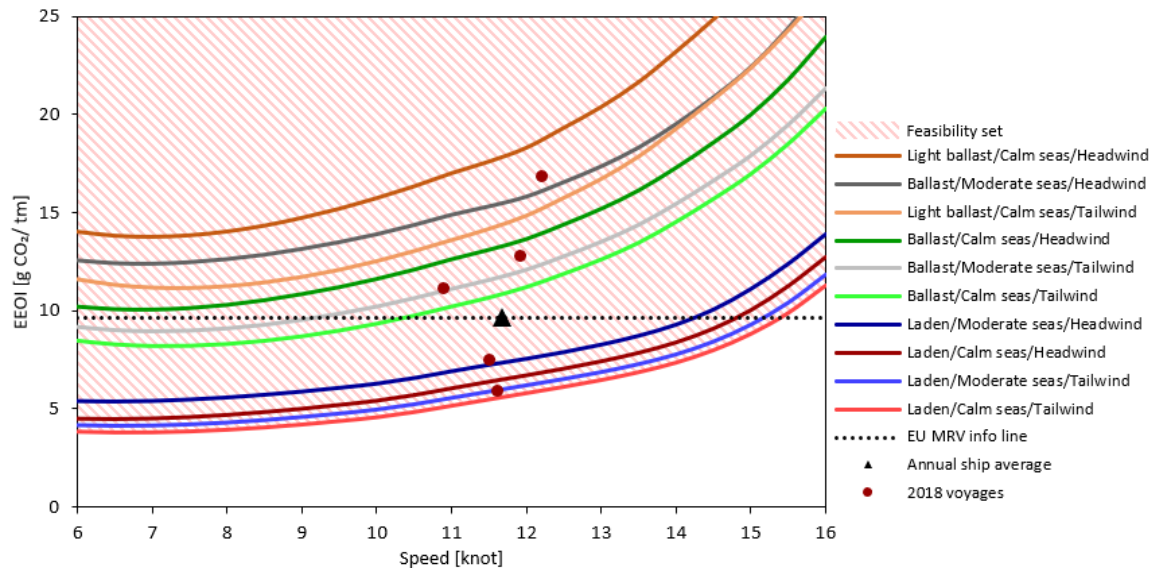


Figure 9. The effect of loading and weather conditions on the EEOI of DryBulk_4
Source: Own compilation

It is worth noting that the EEOI values of 'ballast' and 'light ballast' curves of Figure have been calculated as if the corresponding ballast water was cargo, so they correspond to partly loaded conditions. Under ballasted conditions, the EEOI cannot be defined (infinite value) and the feasible EEOI set of Figure is the entire space above the lowest curve (laden/calm seas/tailwind). In fact, feasibility extends beyond that shown in Figure, as speed can exceed the range of 6-16 knots, which is why Voyage 5 is not shown. Therefore, given that the average speed is not known, the only information that an average EEOI value can convey is that of the dotted line in Figure. Some questions then remain. Can this dotted line say anything about the energy efficiency of this ship, when the minimum requirement for this is the entire laden/calm seas/tailwind curve? How good of an approximation of this curve is the dotted line? How rational is the decision of chartering a ship based on a dotted line a little lower than that of Figure? Unfortunately, the information needed for benchmarking the energy efficiency of ships cannot be condensed in a single indicator, such as EEOI, no matter how good this indicator might be for measuring the performance of a ship.

The same assumptions mentioned above were used to construct the feasible set of ISPI, the other indicator stipulated by the EU MRV Regulation. Theoretically, feasibility is now bound from above by the worst-case scenario (laden/moderate seas/headwind curve of Figure 1) and from below by the best-case scenario (light ballast/calm seas/tailwind). The fact that two voyage-level values lie outside this range in Figure 1 relates to the role that time-at-berth plays in this indicator. Since ISPI is defined as total emissions per nautical mile sailed, the time in port adds to the emissions without affecting the denominator of this fraction, leading to higher indicator values. In Figure 1, time in port is taken equal to the average share of the time this ship was berthed during 2018. Once again, the EU MRV info line does not say much about the feasibility set, which admittedly is better defined here in comparison to the EEOI one.

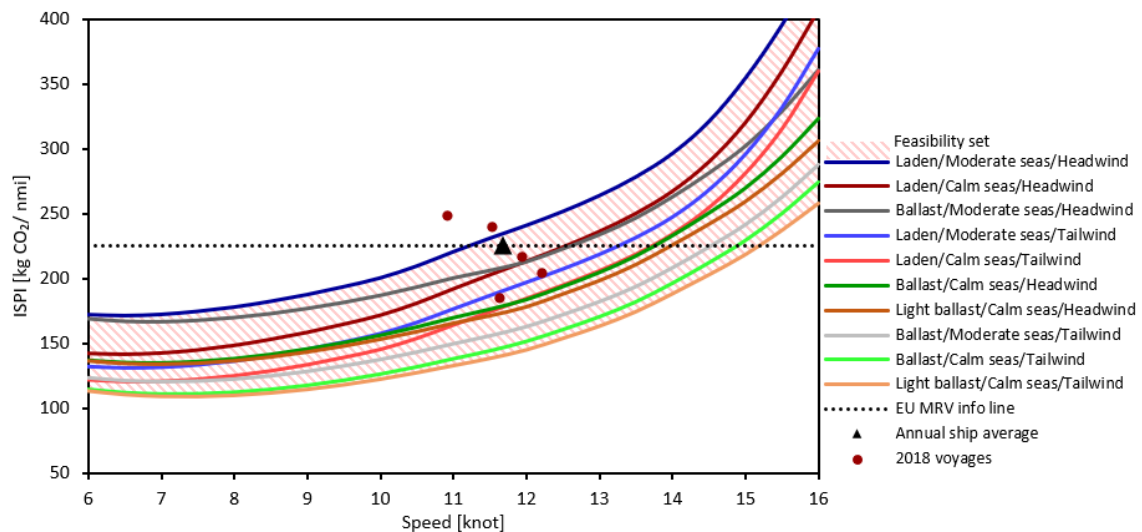


Figure 1. The effect of loading and weather conditions on the ISPI of DryBulk_4
Source: Own compilation

5.6. Comparisons among sister ships

There is always the argument that according to the law of large numbers, the average of the results obtained from a large number of voyages should be close to the expected value of the indicator. To test the validity of this argument, the behaviour of a family of sister ships is examined; the family that includes the ship of the previous case study. As shown in Table 4, there are four sister ships of about 36,800 DWT tonnes that executed at least one voyage on behalf of Company A during 2018. The ship of the previous case study appears as DryBulk_4. The EEOI values at leg and voyage levels are plotted against the corresponding ship-level indicators in Figure 2. Table 4 also presents the mean value of all four indicators and the difference from the mean that each ship exhibits. The same differences are graphically depicted in **Error! Reference source not found..** The EEOI values within the same family range from -14% to 8%, which are nothing but negligible. The variation of the other indicators is of the same order of magnitude.

Table 4. Indicator variation for the sister ships

Ship	N° of Voyages	EEOI			AER			EESH			ISPI		
		Value	Diff. from M	Diff. from WA	Value	Diff. from M	Diff. from WA	Value	Diff. from M	Diff. from WA	Value	Diff. from M	Diff. from WA
DryBulk_1	1	7.66	-14.0%	-17.6%	5.69	-11.3%	-12.5%	2.79	0.0%	1.0%	208.08	-11.6%	-12.8%
DryBulk_2	4	8.87	-0.5%	-4.6%	7.48	16.5%	15.1%	3.00	7.5%	8.5%	275.16	16.8%	15.3%
DryBulk_3	7	9.47	6.2%	1.9%	6.37	-0.8%	-2.0%	2.74	-1.8%	-0.9%	233.07	-1.0%	-2.3%
DryBulk_4	6	9.65	8.3%	3.8%	6.14	-4.4%	-5.6%	2.63	-5.6%	-4.7%	225.67	-4.2%	-5.4%
Mean (M)		8.91			6.42			2.79			235.49		
Weighted average (WA)		9.29			6.50			2.76			238.57		

Source: Own compilation

Not even the ship with the highest number of voyages (DryBulk_3 in the case of EEOI) is the closest one to the mean. If, however, we calculate weighted average figures using the number of voyages as weights, the DryBulk_3's numbers are consistently the closest ones to these averages, which, of course, is not a surprise. This observation, however, is of limited practical value as the EU MRV data cannot support such calculations.

It is worth noting that when regressing the ISPI values of the family at leg and voyage level for speed, we obtain the expected upward moving trend, as shown in Figure 3.

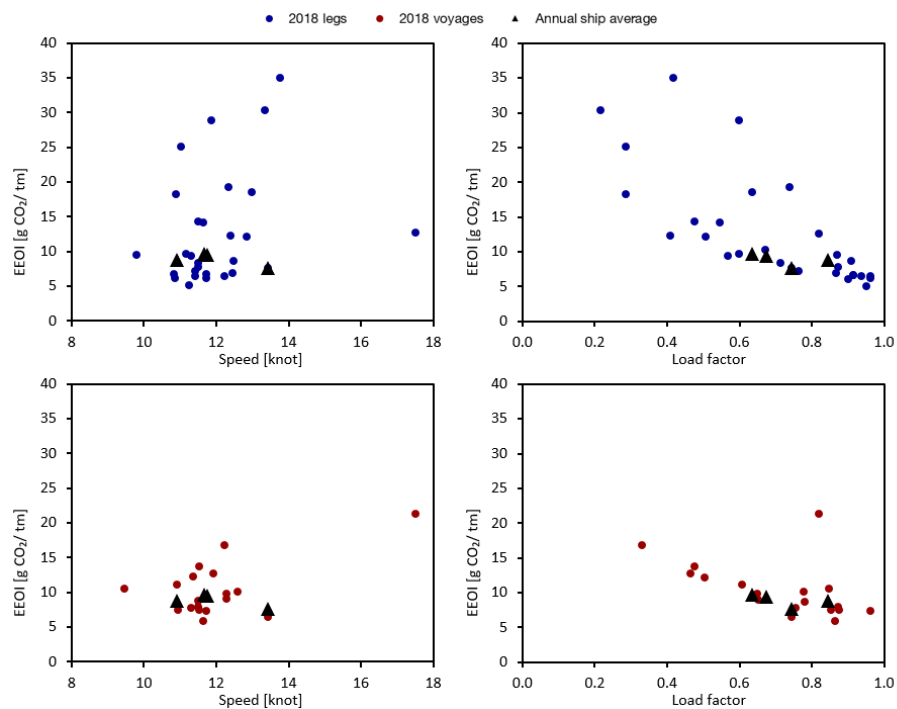


Figure 2. The EEOI for the sister ships' legs and voyages by speed and load factor (2018)
Source: Own compilation

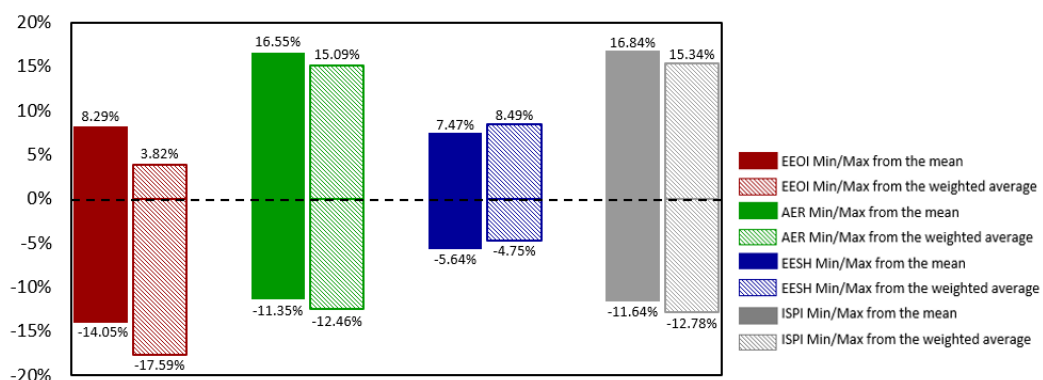


Figure 12. Differences between voyage-level values and the mean/weighted average of indicator values for sister ships
Source: Own compilation

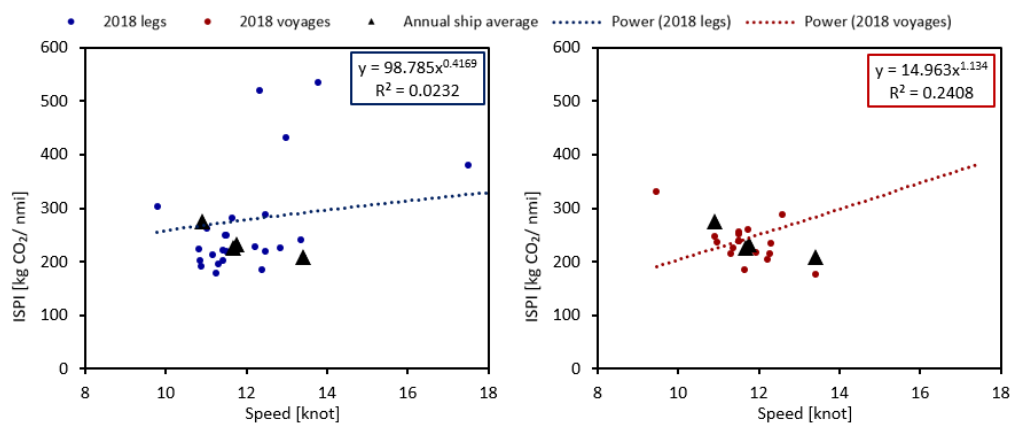


Figure 3. The ISPI values for the sister ships' legs and voyages by speed (2018)
Source: Own compilation

5.7. Geographical coverage

This section investigates the influence of the geographic coverage imposed by the EU MRV Regulation, which concerns only voyages to, within, and from EU ports. The analysis, thus, relates only to the EEOI and ISPI indicators stipulated by the EU MRV Regulation. Figure 4 and 15 present, respectively, the annual EEOI and ISPI values at ship level for both non-EU (in red) and EU (in blue) coverages. The graphs show significant differences that question the accuracy of the reported MRV data. More specifically, the EEOI values at EU level are much lower than those of the same ships when all voyages performed within the year are included in the calculation irrespective of geographical coverage (regression curve in green). A probable explanation relates to the load factor of the respective voyages. As Europe is a major consumer of bulk commodities, the ships of this type tend to exhibit better capacity utilisation around this part of the world. For example, in the case study of Section 5.5, the legs of the higher load factors are those destined to EU ports. This is confirmed by the descriptive statistics of Table 5, where the average cargo carried in EU territory is significantly higher than the average figure outside the EU, when considering only ships that serve both regions.

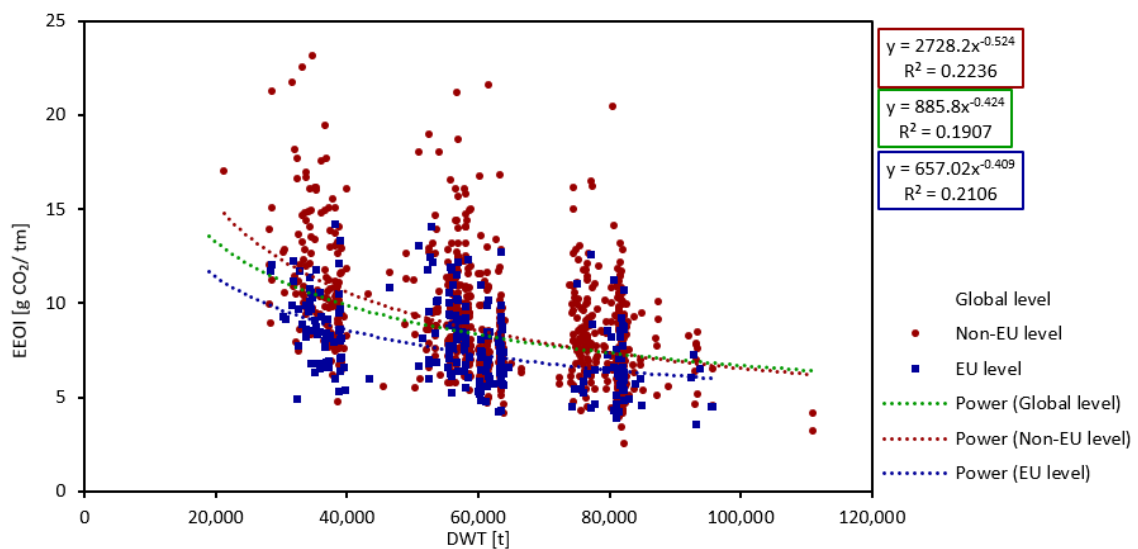


Figure 4. The geographical coverage effect on the EEOI of the sample fleet (2018)
Source: Own compilation

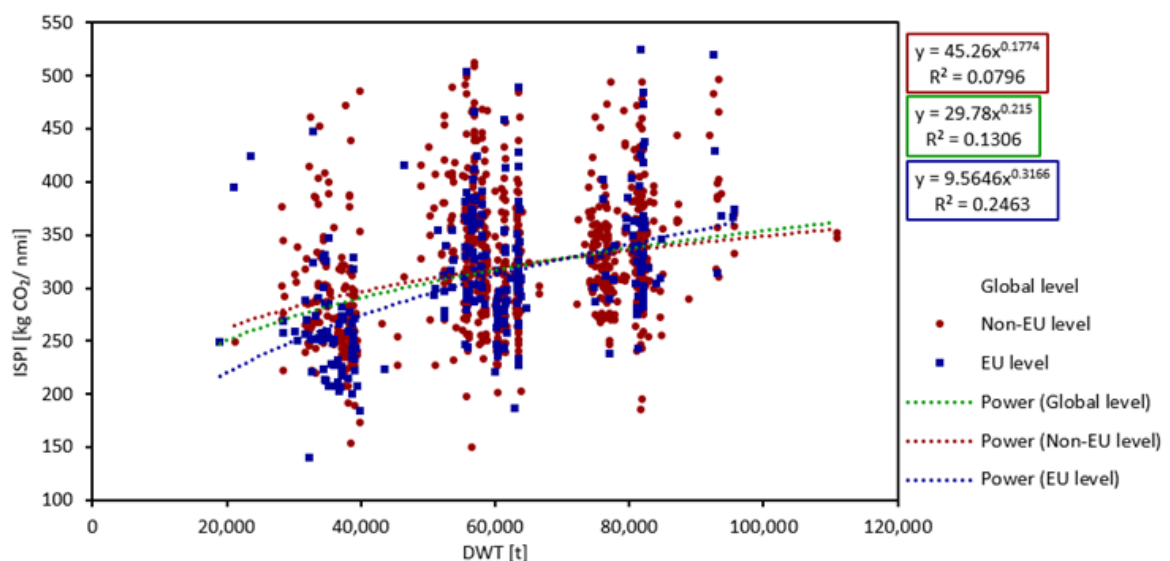


Figure 5. The geographical coverage effect on the ISPI of the sample fleet (2018)
Source: Own compilation

Table 5. Descriptive statistics of Load Factor, EEOI, and ISPI by geographical region

	Load Factor			EEOI			ISPI		
	Global	Non-EU	EU	Global	Non-EU	EU	Global	Non-EU	EU
Mean	0.66	0.65	0.74	8.7	9.0	7.8	321.5	324.6	310.4
Median	0.67	0.65	0.76	8.3	8.4	7.5	316.5	318.4	303.4
Std. Dev.	0.16	0.17	0.14	2.6	3.1	2.1	57.6	60.0	64.4
Minimum	0.28	0.19	0.30	2.6	2.6	3.5	149.3	150.4	140.4
Maximum	0.99	0.99	0.97	19.7	23.2	14.2	509.5	512.4	524.6

Source: Own compilation

As such, the geographical restriction of the EU MRV Regulation introduces an exogenous bias on the reported energy efficiency indicators that further weakens their utility when it comes to providing accurate information to the market players.

6. Conclusion

The paper examines the four most important indicators that have been proposed for monitoring the energy efficiency of shipping operations: EEOI, AER, EESH, and ISPI. The fractions defining all these metrics have a common nominator, the CO₂ emissions generated by the ship during a specific period of time. The metrics differ with respect to their denominator, which is a different expression of transport work.

AER is found to be more robust than EEOI but the use of DWT in place of the actual transport work introduces a significant bias as far as the carbon intensity is concerned. The problem is intensified with EESH and ISPI, which totally ignore the cargo carried.

The results show that none of the indicators examined is robust enough to provide reliable information on the fuel efficiency of ships, which cannot be assessed solely on the basis of an annual average value. In other words, the information needed for benchmarking the energy efficiency of ships cannot be condensed in a single indicator, such as EEOI, no matter how good this indicator might be for measuring the performance of a particular ship. The EEOI would be suitable for monitoring the efficiency of individual ships if properly normalised to nullify the influences of speed, load and possible weather conditions.

Furthermore, the geographical restriction of the EU MRV Regulation introduces an exogenous bias on the reported energy efficiency indicators that further weakens their utility when it comes to providing accurate information to the market players. In this respect, the recent proposal of the Commission to align the MRV Regulation to the DCS monitoring parameters (EU, 2019) is moving in the right direction, although the insistence on transparency should be re-examined in view of the results of Section 5.7. It needs to be noted, however, that the MRV Regulation of the EU has raised the climate consciousness of the sector and played a decisive role among others in the adoption of the global data collection system of the IMO.

The questions that remain unanswered are: (i) Can the formulations of EEOI or ISPI be improved to serve better the MRV objectives? and (ii) how can the energy efficiency of ships be benchmarked after all? It is certain that no single indicator can convey the information needed to assess the energy efficiency of a ship for chartering purposes. Moving into the next phase of the DCS, it will be necessary for the IMO and the research community to develop a set of indicators that address the aforementioned issues.

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