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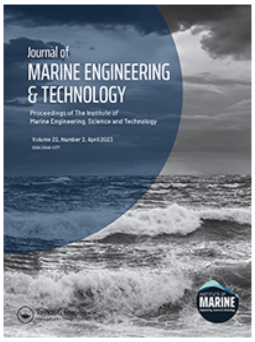

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Operational data-driven energy performance assessment of ships: the case study of a naval vessel with hybrid propulsion

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ABSTRACT
Ship designers hardly ever receive feedback from the actual operation of their designs apart from sea acceptance trials. Similarly, crews operating the vessels do not receive a clear picture of the energy performance and environmental footprint of different options. This paper proposes a methodology based on operational data from continuous monitoring, and applies it to an ocean patrol vessel of the Royal Netherlands Navy in order to identify the impact of diverse operational conditions on energy performance over the whole operating range, but also to examine the decision to equip the vessel with hybrid propulsion. Specifically, it introduces mean energy effectiveness indicator and mean total energy efficiency over discretised vessel speed, as the main tool in quantifying the energy gains and losses to assist in making better-advised design and operational decisions. Moreover, it demonstrates a dataset enrichment procedure, using manufacturers' information, in case not all needed sensors are available. Results suggest that electrical propulsion was 15–25% less efficient than the best mechanical propulsion mode, and on the overall energy performance of the vessel, increasing speed by 1 knot caused a 7% and 14% increase over the minimum CO_2/mile emissions between 8 and 14, and above 14 knots respectively.

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EEDI; EEOI; EEXI; CII; KPI; hybrid propulsion; maritime; data analysis

1. Introduction

The Intergovernmental Panel on Climate Change has concluded that greenhouse gases together with other anthropogenic factors are extremely likely to be the main cause of global warming and climate change (IPCC 2014). Future economic growth and transport demand indicate that maritime carbon dioxide emissions will increase between 50% and 250% by 2050 compared to the 2012 level (IMO 2014). At the same time, legislation on energy efficiency enhancement and emissions, such as the IMO Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) aim to reduce carbon dioxide concentration. However, a reduction in greenhouse gas emissions from shipping, within the same time interval, is only expected in the most conservative and strict scenario.

1.1. Literature review

Mitigation of this environmental problem requires measures that according to Psaraftis (2012) can be described as technological, operational and market-based. Focusing on the first two categories, Vergara et al. (2012) and Bouman et al. (2017) demonstrated the results of numerous studies regarding various ship types. Those studies suggest that the combined implementation of different technologies can reduce carbon dioxide emissions in 2050 by 75%, but no single measure is sufficient in achieving maritime sector goals.

The most important technological measure is the use of alternative fuels like carbon-neutral synthetic fuels, biofuels, hydrogen, and ammonia. Their adoption requires the development of cost-effective power supply systems, and design solutions to storage space and weight issues (van Biert et al. 2016). According to Horvath et al. (2018), hydrogen fuel cells are likely to be economically competitive against fossil internal combustion engines for certain ship types and sizes by 2040, if they follow their current projected development. On the contrary, all other examined power supply options require the implementation of a carbon dioxide cost in order to achieve the same goal. Technological solutions also consider the selection of different system architecture and control strategy, as discussed by Geertsma et al. (2017). Finally, improved hull design, reduced resistance and propulsion augments are expected to provide further savings.

Supplementary to technological measures, a plethora of operational measures such as optimal fleet capacity utilisation, optimal ports operation and better-advised crew decisions, can provide similar or even higher savings. According to Bouman et al. (2017), in particular, weather-based route planning and execution can reduce carbon dioxide emissions by up to 48%, optimal draught and trim selection up to 10%, and vessel speed optimisation up to 60%.

When evaluating energy performance, naval architects come across a high uncertainty level regarding the energy performance assessment of their implemented designs (Vrijdag 2014; Tillig et al. 2018; Vrijdag et al. 2018). Required propeller thrust while sailing at a certain vessel speed is one of the main contributors to this uncertainty, which is transferred to the propulsion plant by the component interaction mechanism described by Stapersma and Woud (2005). The main factors causing the uncertainty in propeller thrust are weather conditions, which show strong geographical and seasonal variation, loading conditions (Coraddu et al. 2017), fouling level (Coraddu et al. 2019a, 2019b), acceleration phases (Mizythras et al. 2018) and manoeuvring activity (Haseltalab and Negenborn 2019b). Aiming to demonstrate the extent of this issue, some studies present their results for a number of resistance-thrust

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curves, as in the case of Geertsma et al. (2017, 2018), where three curves corresponding to trial, design and off-design operational conditions were used, while other studies try to find thrust curve bounds as in the case of Haseltalab and Negenborn (2019a). It is more common though, for authors to assume resistance in calm water with no hull fouling, obtained either from towing tank model tests or from using systematic series and empirical formulas (Harvald 1983; Molland et al. 2011), and evaluate added resistance according to ITTC (2008) as in Shi et al. (2010) and Sui et al. (2019).

Nomenclature

bsfc	brake-specific fuel consumption
CII	carbon intensity indicator
CPP	controllable pitch propeller
DGEN	diesel generator set
EEDI	energy efficiency design index
EEOI	energy efficiency operational indicator
EEXI	energy efficiency existing ship index
GB	gearbox
IMO	international maritime organisation
IPMS	integrated platform monitoring system
MDE	main diesel engine
PTI	power take-in electrical motor
Greek symbols	
δt	dataset time step
η_e	main diesel engines energy efficiency
η_{gb}	gearboxes energy efficiency
η_{gen}	diesel generators energy efficiency
$\eta_{propulsion}$	propulsion energy efficiency
η_{prop}	propellers energy efficiency
η_{psh}	propeller shafts energy efficiency
η_{supply}	power supply energy efficiency
η_{tot}	total energy efficiency
ρ	water density
ζ	energy effectiveness
Latin symbols	
$\dot{m}_{f,e}$	main diesel engines fuel consumption
$\dot{m}_{f,gen}$	diesel generators fuel consumption
d	covered distance
D	propeller diameter
f_{CO_2}	carbon factor
h^L	fuel lower heating value
J	advance coefficient
$K_{Q,ow}$	open water torque coefficient
K_T	thrust coefficient
$M_f(v)$	amount of fuel consumed while sailing at constant speed v
M_{psh}	propeller shaft torque
$M_{CO_2}(v)$	amount of carbon dioxide emissions while sailing at constant speed v
N_i	number of measurements of a certain value
n_{psh}	propeller shaft speed
n_{pti}	electrical motor speed
N_{tot}	total number of measurements at constant speed v
n_{virt}	propeller virtual shaft speed
n_e	main diesel engine speed
p	propeller pitch
p_0	propeller zero thrust pitch
P_{gen}	diesel generators power
$P_{loss,gb}$	gearboxes power losses
$P_{loss,psh}$	propellers shaft power losses
p_{nom}	propeller nominal pitch
P_{psh}	propeller shaft power
P_{pti}	electrical motors power
P_{sh}	intermediate shafts power
P_{TE}	effective thrust power
P_e	main diesel engines power
P_Q	delivered to the propellers power
P_T	propellers thrust power
$Q_{f,e}$	main diesel engines heat flow
$Q_{f,gen}$	diesel generators heat flow
$Q_{f,tot}$	total heat flow
R	actual vessel resistance
R_{tow}	vessel towing resistance
T	propellers thrust
t	thrust deduction factor
T_{req}	required thrust at constant vessel speed
v_{log}	vessel speed through water
v_a	water speed in the ship's wake
W	typical transferred weight
w	Taylor's wake fraction
	Subscripts
μ	mean value
σ	standard deviation value
cpd	carbon per distance
fpd	fuel per distance

Another challenge in the design phase is the prediction of the vessel's speed profile. As mentioned by Georgescu et al. (2018), design objectives related to the power supply and propulsion system change at different design phases and the operational profile knowledge level changes as well. System architecture selection at the concept design phase relies significantly on the amount of time spent sailing at various speeds, but unfortunately, this knowledge is limited at that stage and its estimation can prove to be difficult, especially for naval vessels. This is also the case with decisions at a later phase of the design process, such as component sizing, control strategy selection (Geertsma et al. 2017; Kalikatzarakis et al. 2018), and subsystem working parameters optimisation (Baldi et al. 2015; Shu et al. 2017). Focusing on the aforementioned importance of the operational profile, Yrjänäinen et al. (2019) proposed a profiling tool based on high fidelity model-based simulations taking into account historical weather data and task-oriented split of the whole vessel's mission requirements. Ultimately, Jafarzadeh and Schjølberg (2018) presented the effect of the operational profile at a fleet level, by analysing the profiles for the majority of vessel types sailing in Norwegian waters, while examining hybrid propulsion integration.

IMO aims to enforce and stimulate the reduction of greenhouse gas emissions by requiring a reduction of the Energy Efficiency Design Index (EEDI) of newbuild vessels compared to vessels of the same class, type and deadweight, over time. This index indicates the carbon dioxide emissions per transported capacity and distance (Marine Environment Protection Committee 2011). The EEDI fundamentally qualifies the energy efficiency of a vessel on one design speed, which does not account for the diversity of the operating profile of multifunction ships, such as naval vessels, dredging vessels, offshore and windfarm construction vessels and heavy crane vessels. In order to ensure a balanced design over the vessel's operating profile alternative design indices are required. To establish the vessel's operating profile, data collection and data analysis of similar type vessels should be used.

Similarly, IMO aims to enforce and stimulate the reduction of greenhouse gas emission with a Ship Energy Efficiency Management Plan (SEEMP) during operation, in which the aforementioned operational measures can be implemented. In order to evaluate the effectiveness of those operational emission reduction measures, the Energy Efficiency Operational Indicator (EEOI) is voluntarily used.

This indicator also expresses the amount of carbon dioxide emissions for transporting a certain cargo weight over a certain distance, referring though to the average value over a certain number of voyages (Marine Environment Protection Committee 2009). While useful for evaluating the average emissions for cargo vessels, the method is less valuable for ships with a diverse operating profile, as the uncertainty of the operating speeds in combination with the uncertainty of the operating conditions hinders fair comparison between different missions.

Additionally, the Marine Environment Protection Committee (2021) decided in June 2021 to adopt two new mandatory energy performance evaluation measures. The Energy Efficiency Existing Ship Index (EEXI) which will serve as the EEDI for all existing ships at the time the resolution comes into force, and the annual operational carbon intensity indicator (CII) which will assess the carbon dioxide footprint of vessels on a yearly basis.

1.2. Aim and contribution

Both thrust requirement and vessel speed profile heavily influence the working points of the propulsion and power supply systems, hence the energy performance of vessels. On the contrary, energy performance assessment of new and existing designs, using EEDI and EEXI, respectively, does not account for the changes in energy performance over the range of actual operational conditions and speeds and thus leads to suboptimal designs (Vassalos et al. 2014). Moreover, the suggested operational energy performance assessment methodologies for all ships using EEOI and CII, although offering a quantification tool for the different carbon dioxide emissions level within a certain time window, they fail to provide insight on how operational conditions influence attained energy performance as partly demonstrated in Sun et al. (2013).

This paper introduces an operational data-driven methodology for the energy performance assessment of ships and it is an extension to the first author's earlier work presented at the 15th International Naval Engineering Conference (INEC) in 2020 (Vasilikis 2020). It describes the method in a complete and reproducible manner, it presents additional results on the use of the different operational modes, adding to the insight the method provides, and it also demonstrates its limitations. The novelty of this paper is fivefold:

- It casts light on the actual operational conditions under which vessels, especially multifunction ones, operate.
- It presents a method for enriching an operational dataset in case key parameters are missing, using well-established models.
- It uses the resulting dataset to evaluate the energy performance of the vessel over the whole operational range, not only examining a limited number of operating points.
- It introduces suitable energy performance indicators and visual tools in order not only to assess the previous operation of the vessel, but also in order to assist in enhancing its future performance.
- It examines the impact of design and operational decisions on the resulting energy performance of vessels equipped with hybrid propulsion.

In this way, this paper provides the missing feedback to both designers and users, as seen in Figure 1.

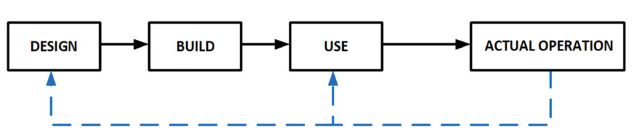


Figure 1. Missing feedback to designers and users in the maritime industry, addressed in this paper.

2. Case study system description

The proposed methodology is suitable to investigate the energy performance of ships with electrical propulsion, ships with mechanical propulsion and ships with hybrid propulsion, equipped either with fixed or controllable pitch propellers. It requires data from the ship's monitoring system platform at a regular sampling frequency, typically 1 to 3 s. The minimum required parameters are illustrated in Figure 2 as measured parameters. In this paper, the methodology is demonstrated with data from a case study patrol vessel, equipped with hybrid propulsion and controllable pitch propellers, as described below.

2.1. Case study vessel

The examined vessel is a *Holland* class ocean patrol vessel (OPV) of the Royal Netherlands Navy (RNLN). Its hybrid propulsion system architecture, seen in Figure 2, consists of two controllable pitch propellers driven either mechanically by one or two main diesel engines or electrically by two electrical motors. Two gearboxes reduce shaft speed and finally three diesel generators produce required electrical power. Component rating and characteristics can be found in Table 1.

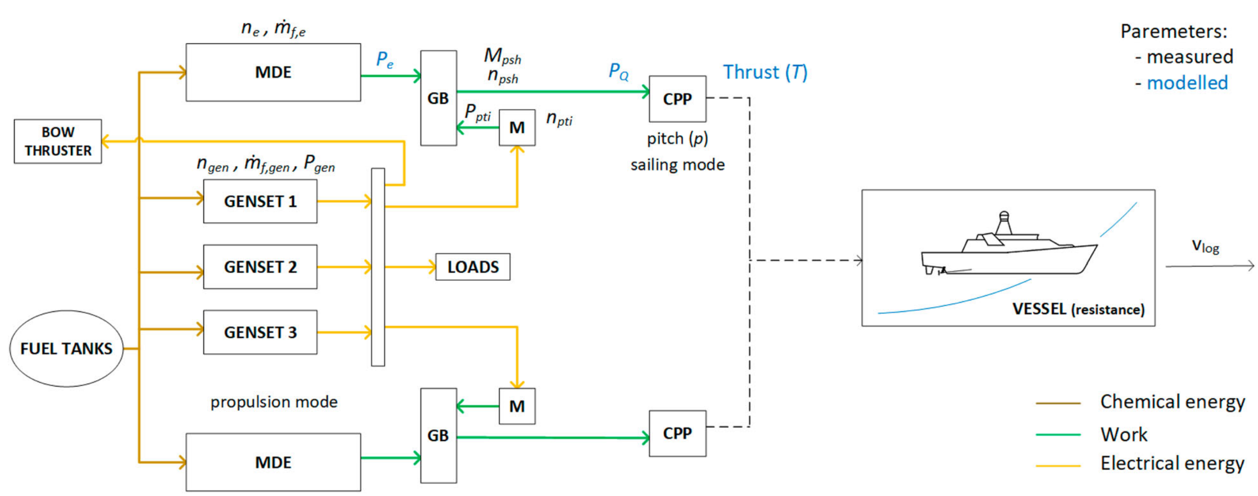


Figure 2. Depiction of the vessel's power system with measured and modelled parameters.

In order to meet diverse mission requirements, a number of operational modes can be selected, as seen in Table 2. The discussion on the optimal use of these modes takes place in Section 4.

2.2. Case study dataset

The Integrated Platform Monitoring System (IPMS) installed on the vessel provides continuous monitoring capabilities for a large number of operational parameters, significantly improving the accuracy of energy performance evaluation over other means, such as noon reports (Aldous et al. 2015). The dataset used in this analysis consisted of 13,276,800 measurements at a 3 seconds time step δt, corresponding to 15 months of operation. The 13 parameters included in this analysis are listed in Table 3. In order to clean the data, the dataset was split into a number of voyages rejecting data corresponding to periods that the vessel was out of operation. Some of the voyages were rejected too for containing periods of faulty sensor functioning. This resulted in processing a total number of 3,400,686 measurements per parameter or about 4 months of actual sailing operation.

2.3. Dataset restrictions

The available dataset does not include parameters for propeller thrust, main diesel engine power and power delivered to the propeller as seen in Figure 2. This means that the energy efficiency of the main diesel engines and propellers cannot be directly evaluated using only measured parameters, since knowledge of the input and output power level of each component is needed. All these three parameters were modelled using the available working point parameters and manufacturers' data. Propeller thrust prediction model was the most complex of all because of the higher number of derived parameters used in corresponding diagrams.

The use of first-principle models based on manufacturers' data of the performance in factory acceptance conditions assumes the components maintain performance under healthy condition. Therefore, the resulting extended dataset cannot be used to evaluate component energy efficiency degradation. Moreover, the effect of system degradation in the used dataset is expected to be limited, as data was collected during the first 15 months of vessel life. In order to evaluate component, subsystem and system energy efficiency degradation, the following additional sensors should be installed:

- Thrust sensor on the propulsion shaft. This would enable us to more accurately establish thrust and evaluate propeller degradation separate from hull fouling and the effect of weather conditions.
- Torque sensor or cylinder pressure measurement system to establish engine mechanical or indicated torque and evaluate engine efficiency degradation.
- Torque sensor close to the propeller. This could be replaced by the torque sensor on the output shaft of the gearbox, to evaluate degradation of gearbox and shaftline efficiency as one joint efficiency.

Table 2. Operational modes.

Propulsion mode	Sailing mode
2 MDEs	transit manoeuvring
1 MDE	trailing at full pitch shaft brake at 0-pitch blocked shaft at full pitch
2 PTIs	

Table 3. Logged IPMS parameters used.

Parameter	Symbol
Main diesel engine speed	n_e
Main diesel engine fuel consumption	$\dot{m}_{f,e}$
Diesel generators speed	n_{gen}
Diesel generators power	P_{gen}
Diesel generators fuel consumption	$\dot{m}_{f,gen}$
PTI motor speed	n_{pti}
PTI motor power	P_{pti}
Propeller shaft speed	n_{psh}
Propeller shaft torque	M_{psh}
Propeller pitch	p
Vessel speed through water	v_{log}
Propulsion mode	–
Sailing mode	–

3. Methodology

This paper proposes a novel operational data-driven energy performance assessment methodology that uses logged measurements of a ship's monitoring system. First, the method enriches the data by using manufacturers' specifications and figures to evaluate parameters that were not directly measured. Subsequently, the instant value of a number of energy performance parameters is evaluated at a vessel, power supply and propulsion subsystems, and component level. Finally, mean values and standard deviations of those parameters over discretised vessel speed or main diesel engine speed are used to explore the contributing factors to a vessel's energy performance and CO_2 footprint.

3.1. Dataset enrichment

Figure 3 presents the manufacturers' data that were used in order to overcome the dataset restrictions discussed in Section 2.3. Gearbox losses can be found in Figure 3(a), propeller shaft losses in Figure 3(b), actual propeller open water diagrams in Figure 3(c and d), the relation between propeller pitch command and pitch to diameter ratio in Figure 3(e), and finally wake fraction data from towing tank tests in Figure 3(g).

First, propeller shaft power P_{psh} was evaluated in kW using corresponding torque M_{psh} in kNm and speed n_{psh} in rad/s, as follows:

$$P_{psh} = M_{psh} n_{psh}. \tag{1}$$

Table 1. Power supply and propulsion system components.

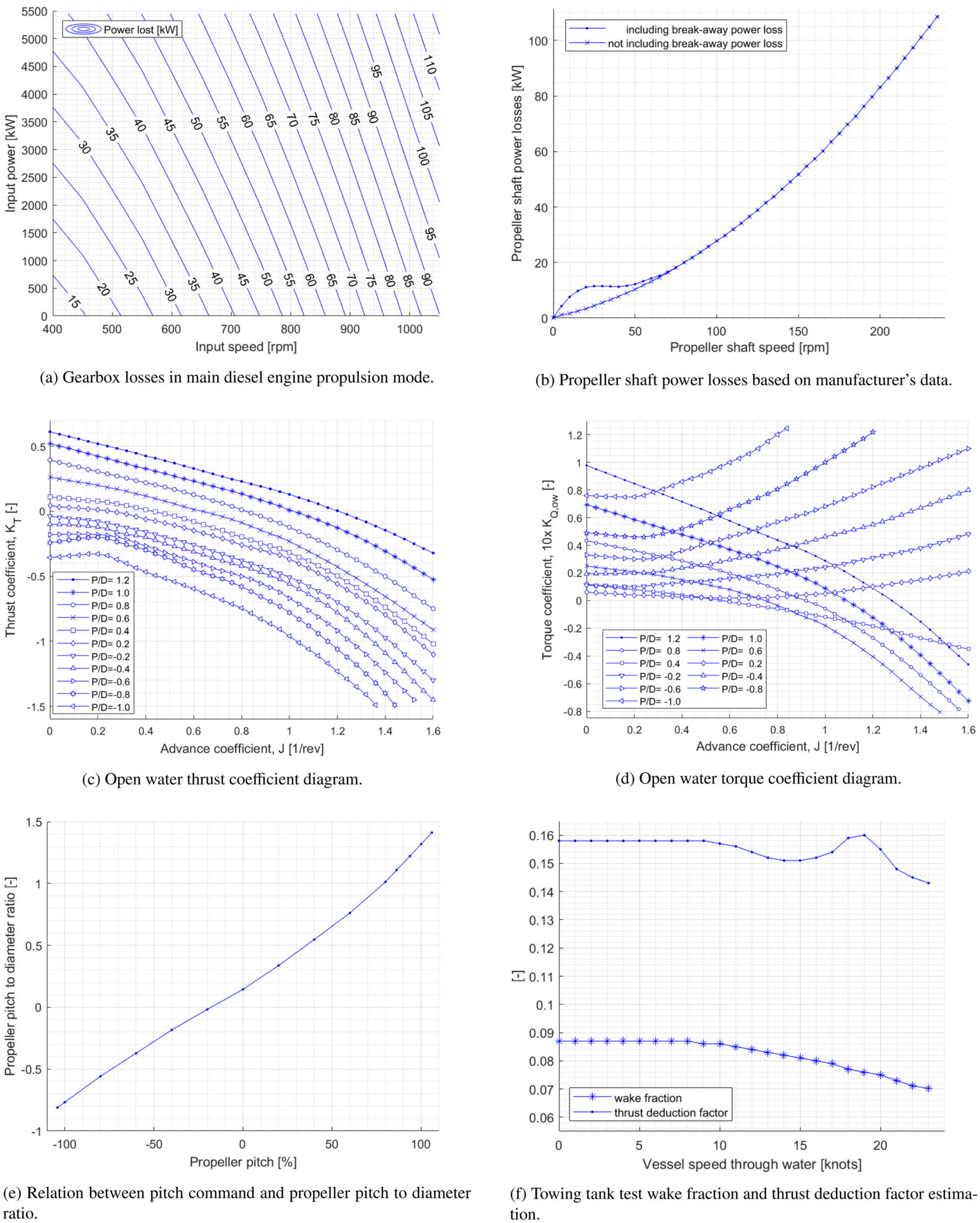
Main diesel engines		**Gearboxes**		**CPP propellers**	
nominal power	5400 kW	reduction ratio (MDE)	4.355	diameter	3.2 m
nominal speed	1000 rpm	reduction ratio (PTI)	17.880	number of blades	5
				pitch/diameter ratios	
Diesel generator sets		**PTI motors**		−100% ahead	1.318
nominal power	910 ekW	nominal power	400 kW	– design	1.108
nominal speed	1800 rpm	nominal speed	1788 rpm	−100% astern	−0.768

Then, power delivered by the main diesel engines P_e, accounting for gearbox losses $P_{loss,gb}$, in kW is given from:

$$P_e = P_{psh} + P_{loss,gb}. \tag{2}$$

Power delivered to the propeller P_Q was evaluated afterwards, accounting for shaft losses $P_{loss,psh}$, in kW from:

$$P_Q = P_{psh} - P_{loss,psh}. \tag{3}$$



(a) Gearbox losses in main diesel engine propulsion mode.

(b) Propeller shaft power losses based on manufacturer's data.

(c) Open water thrust coefficient diagram.

(d) Open water torque coefficient diagram.

(e) Relation between pitch command and propeller pitch to diameter ratio.

(f) Towing tank test wake fraction and thrust deduction factor estimation.

Figure 3. Information provided by the component manufacturers and the shipbuilder. (a) Gearbox losses in main diesel engine propulsion mode, (b) Propeller shaft power losses based on manufacturer's data, (c) Open water thrust coefficient diagram, (d) Open water torque coefficient diagram, (e) Relation between pitch command and propeller pitch to diameter ratio and (g) Towing tank test wake fraction and thrust deduction factor estimation.

Propeller thrust T in kN and thrust power P_T in kW are established using the following relations:

$$T = K_T \rho n_{psh}^2 D^4, \quad (4)$$

$$P_T = T v_a, \quad (5)$$

where ρ is the saltwater density equal to 1025 kg/m^3, D is propeller diameter in m and v_a water speed in the ship's wake in m/s, obtained from vessel speed through water v_{log} in m/s and Taylor's wake factor w as:

$$v_a = v_{log}(1 - w). \quad (6)$$

Thrust coefficient K_T was evaluated by reading the corresponding propeller open water diagram with advance coefficient J and pitch to diameter P/D values. Advance coefficient J was evaluated from:

$$J = \frac{v_a}{n_{psh} D}, \quad (7)$$

Another important parameter evaluated is effective thrust power P_{TE} in kW, as seen in Figure 4:

$$P_{TE} = T v_{log} = \frac{T v_a}{(1 - w)} = \frac{P_T}{(1 - w)}, \quad (8)$$

and finally, required propeller thrust T_{req} in constant speed sailing was evaluated as a reference for obtained results, using ship towing resistance R_{tow} and thrust deduction factor t from towing tank tests, as:

$$T_{req} = R = \frac{R_{tow}}{1 - t}. \quad (9)$$

3.2. Power system energy efficiency

The majority of ships use fossil fuels in order to meet their power supply needs. The three main consumers on each ship in descending order are its main and auxiliary engines, and its boilers. Boilers' contribution is almost negligible for all vessel types except for oil tankers (IMO 2014). In conventional maritime power systems, chemical energy saved in fuels is released as heat through combustion. Main engines, most often diesel engines, convert this heat into work and provide it to the propellers either directly or through reduction gearboxes. Then, propellers turn this work into propulsion thrust in order to counter vessel resistance and accelerate the vessel. Auxiliary diesel engines on the other hand convert heat to work, work to electrical power and provide it to the electrical grid of the ship. These power conversions and transmissions introduce a number of component, subsystem and whole system energy efficiencies, which in this study are evaluated from measured and derived parameters as described in Section 3.1.

3.2.1. Component-level

Main diesel engine efficiency η_e is defined as:

$$\eta_e = \frac{P_e}{Q_{f,e}} = \frac{P_e}{\dot{m}_{f,e} h^L}, \quad (10)$$

where $Q_{f,e}$ is heat flow released from fuel combustion in kW, $\dot{m}_{f,e}$ is fuel consumption in kg/s and h^L stands for fuel lower heating value assumed equal to 42,500 kW/kg. Diesel generator set efficiency η_{gen} is defined in a similar way:

$$\eta_{gen} = \frac{P_{gen}}{Q_{f,gen}} = \frac{P_{gen}}{\dot{m}_{f,gen} h^L}, \quad (11)$$

where P_{gen} is the electrical power provided in kW, $Q_{f,gen}$ corresponds to heat flow in kW and $\dot{m}_{f,gen}$ to fuel consumption in kg/s. Gearbox efficiency η_{gb} is defined as:

$$\eta_{gb} = \frac{P_{psh}}{P_{sh}}, \quad (12)$$

where P_{psh} is the power delivered to the propeller shaft in kW and P_{sh} is the power provided by the main diesel engines or the electrical motors to the intermediate shaft in kW, as follows:

$$P_{sh} = \begin{cases} P_e & \text{Other modes} \\ P_{pti} & \text{PTI mode.} \end{cases} \quad (13)$$

Propeller shaft efficiency η_{psh} is evaluated using power delivered to the propeller shaft P_{psh} and to the propeller P_Q in kW, as:

$$\eta_{psh} = \frac{P_Q}{P_{psh}}. \quad (14)$$

Finally, propeller efficiency η_{prop} is provided by:

$$\eta_{prop} = \frac{P_T}{P_Q} = \frac{T v_a}{P_Q}, \quad (15)$$

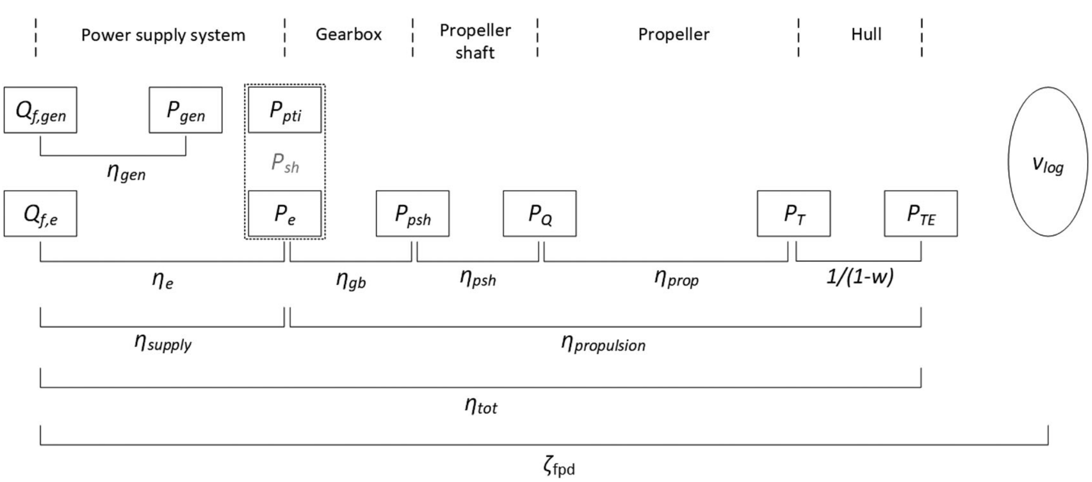


Figure 4. Energy performance indicators and parameters involved.

and open water propeller efficiency $\eta_{\text{prop,ow}}$ using required propeller torque in open water testing conditions $M_{\text{Q,ow}}$ by:

$$\eta_{\text{prop,ow}} = \frac{P_{\text{T}}}{P_{\text{Q,ow}}} = \frac{Tv_{\text{a}}}{M_{\text{Q,ow}} n_{\text{psh}}} = \frac{K_{\text{T}} \rho n_{\text{psh}}^2 D^4}{K_{\text{Q,ow}} \rho n_{\text{psh}}^2 D^4} \frac{v_{\text{a}}}{D n_{\text{psh}}} = \frac{K_{\text{T}}}{K_{\text{Q,ow}}} J. \quad (16)$$

3.2.2. System and subsystem-level

Power supply and propulsion subsystems energy efficiency was evaluated using total heat flow $Q_{\text{f,tot}}$, shaft power P_{sh} for both power supply options are defined in Equation (13), and effective thrust power P_{TE} in kW as:

$$\eta_{\text{supply}} = \frac{P_{\text{sh}}}{Q_{\text{f,tot}}} = \frac{P_{\text{sh}}}{(\dot{m}_{\text{f,e}} + \dot{m}_{\text{f,gen}}) h^L}, \quad (17)$$

$$\eta_{\text{propulsion}} = \frac{P_{\text{TE}}}{P_{\text{sh}}}. \quad (18)$$

Ultimately, energy efficiency of the whole power system was provided by:

$$\eta_{\text{tot}} = \frac{P_{\text{TE}}}{Q_{\text{f,tot}}} = \frac{P_{\text{sh}}}{Q_{f,\text{tot}}} \frac{P_{\text{TE}}}{P_{\text{sh}}} = \eta_{\text{supply}} \eta_{\text{propulsion}}. \quad (19)$$

It must be noted that effective thrust power P_{TE} was selected as the end point of the energy chain defined in Equation (8), instead of effective towing power P_{E} seen in Klein Woud and Stapersma (2002). The main reason is that this analysis examines the dynamic energy performance of the system while sailing under real operational conditions, on the contrary, to static considerations at the design phase, which are established through scale model tests. As a result, a thrust-based power parameter seems more suitable compared to ship's towing R_{tow} or actual resistance R. Moreover, despite the IPMS dataset restrictions described in Section 2.3, thrust parameter T can be directly measured using a thrust sensor. On the contrary, evaluation of actual resistance R requires knowledge of the vessel's actual and hydrodynamic added mass and acceleration. In the case of using towing resistance R_{tow}, which is a theoretical parameter as the vessel is not towed, information concerning thrust deduction factor t is additionally needed.

3.3. Vessel energy effectiveness

Mission requirement of most vessels is the transportation of a certain payload over an indicated distance. This is achieved, as discussed in the previous subsection, by consuming fuel resources in their power systems. Energy efficiency η_{tot} of the whole system provides a good indication of the fraction of resources that turns into useful output, but it does not offer though any information on the amount of resources required by the vessel in the first place. A factor providing resources 'paid' in order to reach a certain transportation level seems more appropriate. Effectiveness, in contrast to efficiency, appears to conceptually describe this difference to an adequate degree, hence is the term selected in this analysis. Figure 5 provides a graphical representation of the used terminology and the influencing factors.

Literature on mechanical engineering applications, specifically on heat exchange applications, determines effectiveness as the ratio of actual heat transfer rate to the theoretical maximum (Kutscher 1994; Narayan et al. 2010), but such a consideration in the case of energy conversion and transmission is already described by exergy or also called rational efficiency (Kotas 1985). Finally, Sui et al. (2019) also discuss the use of this term in the energy analysis of maritime systems but proceed with a different set of definitions.

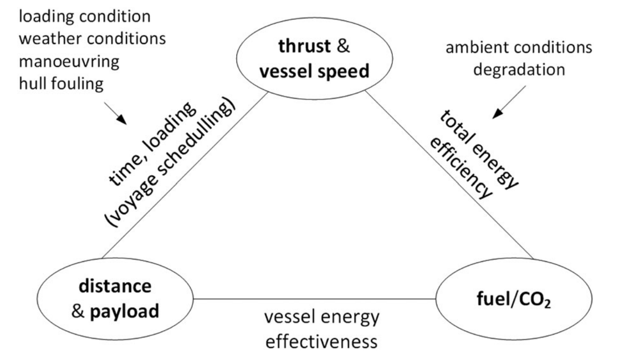


Figure 5. Illustration of the relation between vessel energy effectiveness, total energy efficiency and influencing factors.

In this study, we use in the assessment of the vessel's energy performance, the energy effectiveness indicator defined as:

$$\zeta = \frac{m_{\text{f,tot}}}{Wd} = \frac{\dot{m}_{\text{f,tot}}}{Wv}, \quad (20)$$

where $m_{f,\text{tot}}$ is the total amount of fuel consumed, d is the covered distance, v is vessel speed, and W a typical transportation weight.

When deadweight and displacement do not show significant variation, as in the case of patrol vessels, we can ignore the weight term W and consider covered distance as the main operational benefit. By further not accounting for current effects, vessel speed through water v_{log} is used. Consequently, the energy effectiveness indicator is provided by:

$$\zeta_{\text{fpd}} = \frac{\dot{m}_{\text{f,tot}}}{v_{\text{log}}} = \frac{\dot{m}_{\text{f,e}} + \dot{m}_{\text{f,gen}}}{v_{\text{log}}}. \quad (21)$$

Accounting for the environmental impact and aligned with the indices and indicators introduced by IMO, the cost of sailing can also be expressed by the production of carbon dioxide emissions $\dot{m}_{CO_2}$. The energy effectiveness indicator can also be written then as:

$$\zeta_{\text{cpd}} = \frac{\dot{m}_{CO_2}}{v_{\text{log}}} = \frac{\dot{m}_{\text{f,tot}} f_{CO_2}}{v_{\text{log}}}, \quad (22)$$

where f_{CO_2} is the mass ratio constant between carbon dioxide emissions and fuel. Fuel composition plays an important role in this constant. The first IMO greenhouse gas study (IMO 2000) suggested a value of 3.170 for all fuel types, the second study (IMO 2009) a value of 3.021 for heavy fuel oil and 3.082 for marine gas and diesel oils, while EEDI calculation methodology a value of 3.110.

3.3.1. Mean energy effectiveness indicator and standard deviation

Vessels sail in operational conditions that vary a lot, posing different energy requirements. Application of all previously mentioned energy efficiency and effectiveness indicators results in a population of instant values as seen, for instance, in the case of propeller thrust in Figure 6. Despite the fact that these populations provide the limits of actual vessel operation, they do not offer any information on the achieved energy performance of the vessels.

In order to overcome this issue, this paper introduces weighted mean energy effectiveness indicator ζ_{fpd_μ} and corresponding standard deviation $\zeta_{\text{fpd}_\sigma}$ over discretised vessel speed v as the main energy performance assessment tool utilising operational data, as follows:

$$\zeta_{\mathrm{fpd}_\mu}(v) = \frac{\sum_{i=1}^{n} \zeta_{\mathrm{fpd}_i} N_i}{\sum_{i=1}^{n} N_i}, \tag{23}$$

$$\zeta_{\mathrm{fpd}_\sigma}(v) = \sqrt{\frac{\sum_{i=1}^{n} (\zeta_{\mathrm{fpd}_i} - \zeta_{\mathrm{fpd}_\mu})^2 N_i}{\sum_{i=1}^{n} N_i - 1}}, \tag{24}$$

where ζ_{fpm_i} is one of the n different energy effectiveness indicator values found within limits $[v - \delta v/2, v + \delta v/2)$, and N_i play the role of weights, being the number of measurements for each different value i. The same formulas were used for calculating discretised mean value and standard deviation of every other parameter or energy performance indicator.

Finally, the importance of the mean energy effectiveness indicator can be seen from its relation to the actual amount of fuel consumed while sailing at a certain speed $M_\mathrm{f}(v)$ and the carbon dioxide emissions $M_{\mathrm{CO}_2}(v)$, which are provided by:

$$M_\mathrm{f}(v) = \sum_{i=1}^{n} \dot{m}_{\mathrm{f,tot_i}} N_i \delta t = \dot{m}_{\mathrm{f,tot}_\mu} \sum_{i=1}^{n} N_i \delta t = \frac{\dot{m}_{\mathrm{f,tot}_\mu}}{v} v N_{\mathrm{tot}} \delta t = \zeta_{\mathrm{fpd}_\mu} v N_{\mathrm{tot}} \delta t, \tag{25}$$

and

$$M_{\mathrm{CO}_2}(v) = \zeta_{\mathrm{cpd}_\mu} v N_{\mathrm{tot}} \delta t. \tag{26}$$

Equations (25) and (26) suggest that using an estimation of the mean energy effectiveness indicators $\zeta_{\mathrm{fpd}_\mu}(v)$ and $\zeta_{\mathrm{cpd}_\mu}(v)$ over the whole vessel speed range and of the operational profile $N_{\mathrm{tot}}(v)$, we can estimate the total amount of required fuel and carbon dioxide emissions within a certain time horizon, necessary in life-cycle assessment analyses.

4. Results and discussion

This section presents and discusses the results of the proposed methodology with the case study *Holland* class patrol vessel. First, it discusses the operational uncertainties under which the vessel sailed. Then, it demonstrates the use of mean energy effectiveness indicator in describing the energy performance of the vessel, both within an examined period and for future predictions, and it also stresses the importance of vessel speed profile in life cycle fuel cost assessments. Next, it demonstrates how total system, subsystem and component energy efficiency analysis can be used to improve the design and provide feedback to operators on the available operational modes, and finally, it discusses on the decision to adopt hybrid propulsion by the case study vessel.

4.1. Operational uncertainties

The impact of the various uncertainties that influence the operating profile and, therefore, energy performance of multifunction vessels is best demonstrated by the thrust distribution that the vessel encounters, presented in the dimensions vessel speed and thrust. Figure 6 shows the frequency of occurence, mean value and standard deviation of thrust, against three curves used at the design phase of the vessel. Those curves correspond to trial, design and off-design operational conditions, and they were produced by running model tank tests. Their description is given in Table 4. This figure clearly demonstrates that propeller thrust during normal operating conditions can actually vary as much as 25% of its nominal value, within the one standard deviation range, near full speed and 100% near half speed. This variation is caused by environmental factors like wind and waves, by operational factors like loading condition and rudder activity, by maintenance conditions such as propeller and hull fouling, and also by ship acceleration and deceleration.

The evaluated mean propeller thrust is in good agreement with the design curve, being equal between 8 and 10 knots and within 5% between 7 and 18 knots. Below 7 knots, however, the design curve

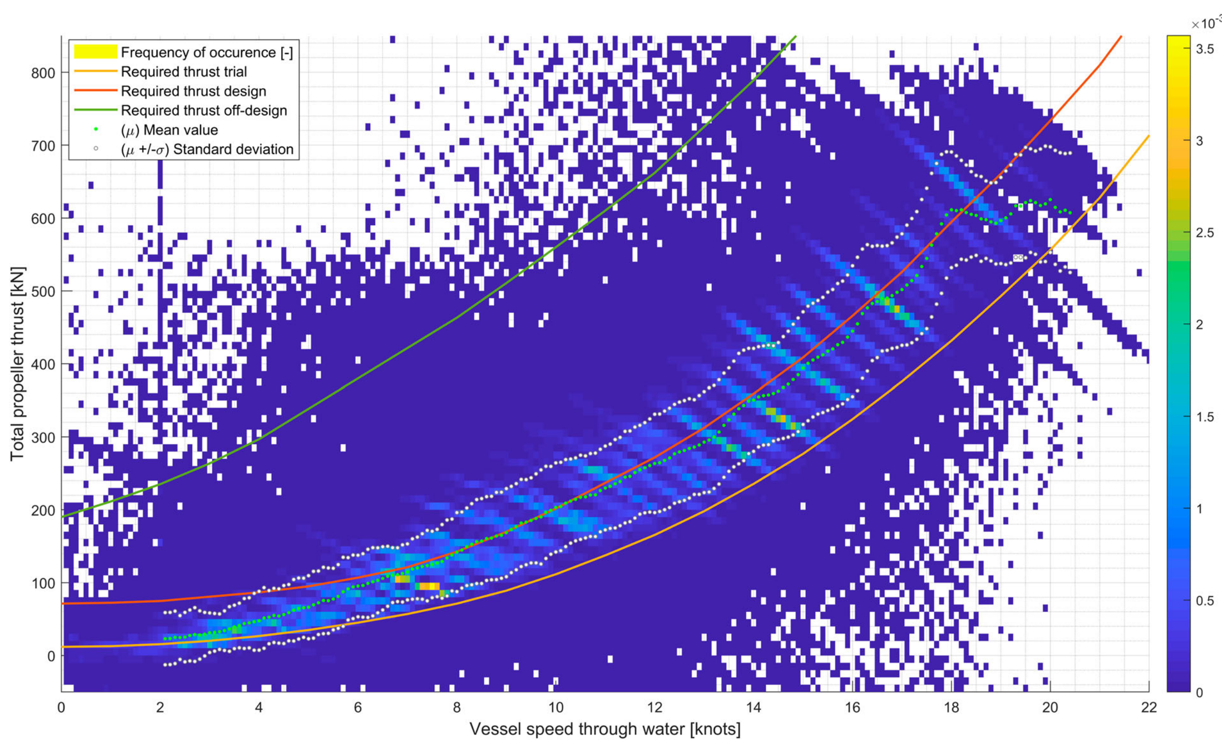


Figure 6. Two-dimensional histogram, mean value, and standard deviation of evaluated total propeller thrust over discretised vessel speed.

Table 4. Reference weather and fouling conditions.

Condition	Sea state	Wind speed	Fouling
trial	0	max 5 knots	no
design	4	max 21 knots (Beaufort scale 5)	6 months out of dock
off-design	6	max 47 knots (Beaufort scale 9)	6 months out of dock

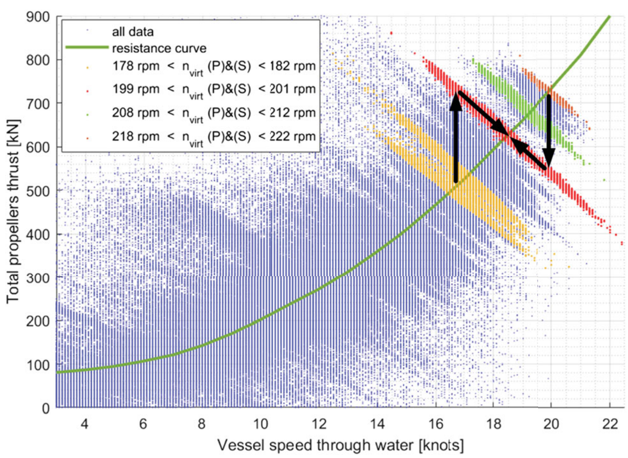


Figure 7. Propeller thrust and vessel speed through water with highlighted areas of bounded virtual shaft speed. Hypothetical acceleration and deceleration phases are also demonstrated.

does not intersect zero thrust at zero ship speed, as it assumes headwind. Therefore, the quadratic fit through the design resistance at an intermediate speed of 7 to 10 knots should be assumed for low ship speeds, up to 7 to 10 knots, to account for wind from all directions, if measured mean value of thrust is not available. Above 18 knots, mean thrust leans towards the trial conditions curve. The resulting mean value of evaluated thrust as a function of ship speed is a good measure for life cycle analysis, as it accounts for the average load over the various ship speeds. Furthermore, we observe that thrust is indeed bounded between the trial and off-design curves, but the vessel hardly ever sailed in such adverse weather conditions as described by the off-design curve. Thus, using this curve as a design driver might be over-conservative.

Figure 6 also shows that the thrust-vessel speed distribution is not uniformly distributed. Diagonal areas of increased frequency of occurrence exist. As demonstrated in Figure 7, these areas refer to constant virtual shaft speed setting, provided by:

$$n_{\mathrm{virt}} = \frac{p - p_0}{p_{\mathrm{nom}} - p_0} n_{\mathrm{prop}}, \tag{27}$$

where p is propeller pitch, p_0 is zero thrust pitch, p_{nom} is nominal pitch and n_{prop} is propeller speed. According to Geertsma et al. (2017), virtual shaft speed, being linearly related to vessel speed is the command provided by the crew to the propulsion system. This means that in order to either accelerate or decelerate to a different sailing speed, an increased or decreased virtual shaft speed is set. Due to vessel inertia, thrust moves to another diagonal under almost constant speed and then speed and thrust balance at the intersection point with the theoretical resistance curve shown in the same figure.

4.2. Vessel's energy performance and CO_2 footprint

This paper introduced the use of the mean energy effectiveness indicator, providing the fuel-carbon resource cost of sailing at a certain vessel speed under various operational conditions, as the main tool in quantifying the obtained energy performance and carbon dioxide footprint of ships within an examined period. It also distinguished between energy effectiveness, and total energy efficiency expressing the ability of the system to exploit a certain amount of fuel resources. Figure 8 visualises this information by presenting mean energy effectiveness indicator and mean total energy efficiency against discretised vessel speed through water.

The results suggest that although mean total energy efficiency gradually increases to its maximum value of 28% near full speed, mean energy effectiveness indicator shows a convex curve behaviour with a minimum value of 44 kg/mile or 137 kg CO_2/mile near 7 knots, and maximum values of 95 kg/mile or 296 kg CO_2/mile and 98 kg/mile or 305 kg CO_2/mile at 2 and 20 knots, respectively. Specifically:

- Below 4 knots, mean energy effectiveness indicator increases by 20 kg/mile or 62 kg CO_2/mile per 1 knot drop.
- Between 4 and 6 knots, mean energy effectiveness indicator increases by 3.5–4 kg/mile or 11-12 kg CO_2/mile per 1 knot drop.
- Between 6 and 8 knots, mean energy effectiveness indicator is almost constant, equal to 45–46 kg/mile or 140 kg CO_2/mile.
- Between 8 and 14 knots, mean energy effectiveness indicator increases by 3 kg/mile or 9.3 kg CO_2/mile per 1 knot increase.
- Above 14 knots, mean energy effectiveness indicator increases by 6 kg/mile or 18.6 kg CO_2/mile per 1 knot increase.

Mean energy effectiveness indicator can also be used in life cycle fuel cost and carbon emissions analyses, when specific operational conditions are not taken into account, coupled with the prediction of the vessel's speed profile, according to Equations (25) and (26).

Figure 8 also presents the difference between the actual vessel's speed profile, which is associated with the high frequency of occurence of certain virtual shaft speed settings shown in Figure 6, and the design profile reported in van Straten and de Boer (2012). The crew sailed more frequently below 10 knots, less frequently between 10 and 14, and more frequently between 14 and 17 knots. It also sailed less above 17 knots, and hardly ever sailed above 20 knots, while the design scenario considered 8% of total sailing time. Figure 9 provides additionally the amount of consumed fuel, based on the attained mean energy effectiveness indicator curve, for the actual and the design profiles. The design scenario, which considered increased fuel consumption by 25%, suggests key sailing speeds of 14–15 and 19–21 knots, while our analysis indicates 14–16, and 17 knots.

4.3. Energy performance on different operational modes

The previous section discussed the use of mean energy effectiveness indicator, instead of EEOI or CII, in the energy performance assessment of ships. Important advantage of our proposed methodology is the additional feedback it provides on the design and use of the different available operational modes, accounting for actual operational conditions.

4.3.1. Description of the available operational modes

The vessel can sail on one of the six different operational modes found in Table 2. Figure 10 provides the resulting combinator curves for the four operational modes used by the crew under normal mission requirements, and Figure 11 the resulting working points of the main diesel engines. Sailing on 2 MDEs manoeuvring mode involves a conservative pitch strategy in comparison to transit mode, resulting in higher propeller speed. The decreased pitch value is a measure against diesel engine overloading, thus manoeuvring mode should be used mainly during operations with high manoeuvrability

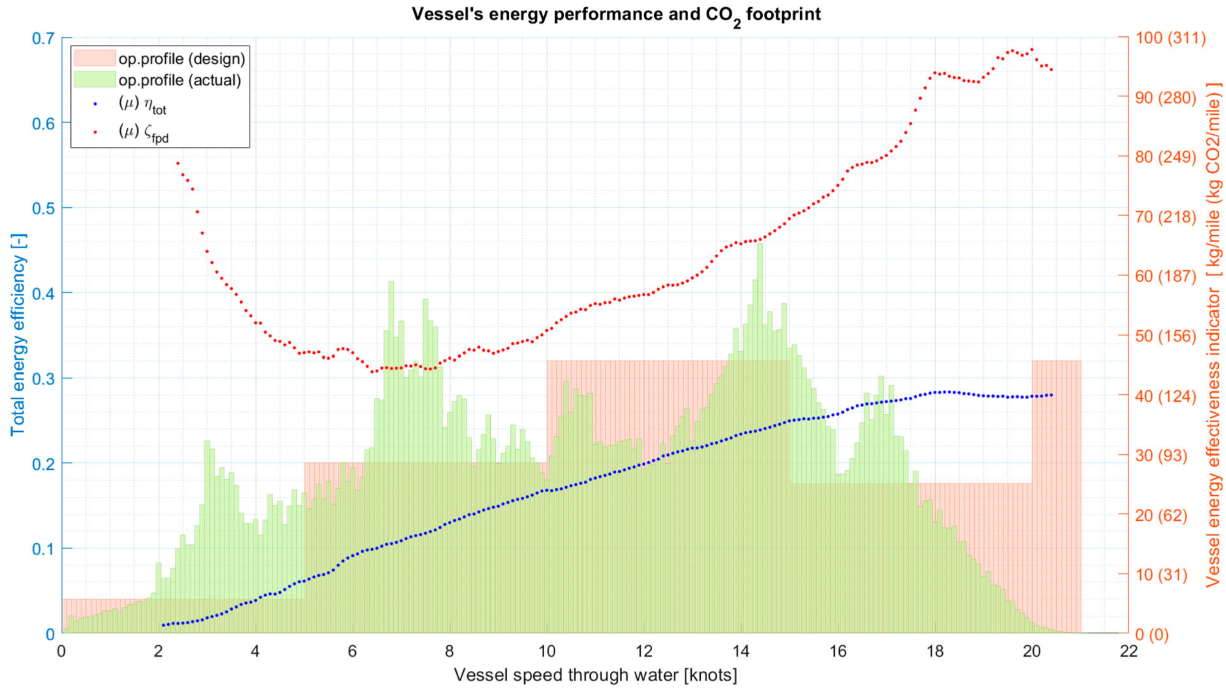


Figure 8. Mean energy effectiveness indicator and mean total energy efficiency over discretised vessel speed, with an additional demonstration of the difference between the design and the actual vessel speed profile.

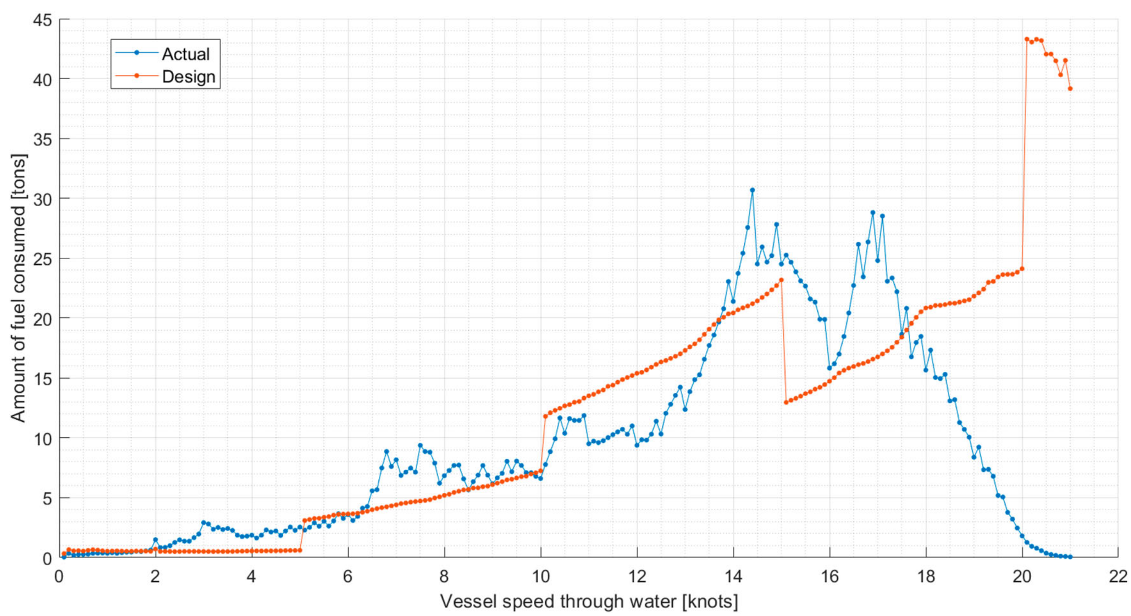


Figure 9. Actual amount of consumed fuel against the hypothetical amount that is evaluated based on the design operational profile and the attained the mean energy effectiveness indicator.

requirements, such as entering and leaving port, close-quarters operations and emergency manoeuvres. 2 PTIs mode, on the other hand, increases directly to maximum pitch, since the electrical motors can provide maximum torque without the risk of overloading. Moreover, 1 MDE trailing mode also involves a conservative pitch strategy compared to the 2 MDEs transit mode, as the whole load is provided by one engine. The trailing shaft is let to move freely at full pitch, although being restricted to maintain at least 50 rpm, thus not allowing sailing below 9 knots. Propelling on one main diesel engine offers another two options regarding the second shaft. 0-pitch mode includes the second propeller to reduce its speed by setting zero pitch. This mode normally precedes the final option of the blocked mode, when the shaft brake brings the second propeller to a full stop at full pitch. 0-pitch and blocked modes are usually selected when the vessel undergoes some kind of propulsion system maintenance. Furthermore, Figure 12 provides how often and at what speed are the operational modes used. 2 MDEs-transit is the most frequently used mode above 12 knots, while 2 PTIs mode is the most frequently used below 9 knots. 2 MDEs-manoeuvring mode is used across almost the whole speed range, although not being the primary choice at any of them. Finally, one main diesel engine operation, especially on trailing mode, is used regularly between 9 and 16 knots.

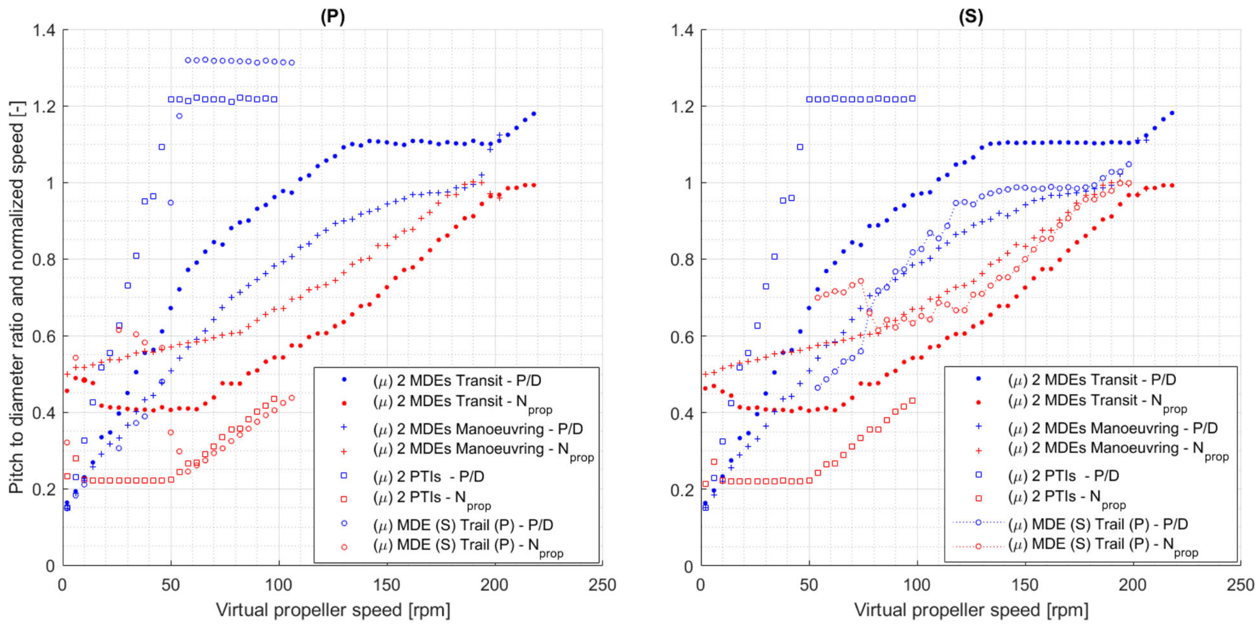


Figure 10. Mean value pitch to diameter and rotational speed over discretised virtual shaft speed of port (P) and starboard (S) propellers.

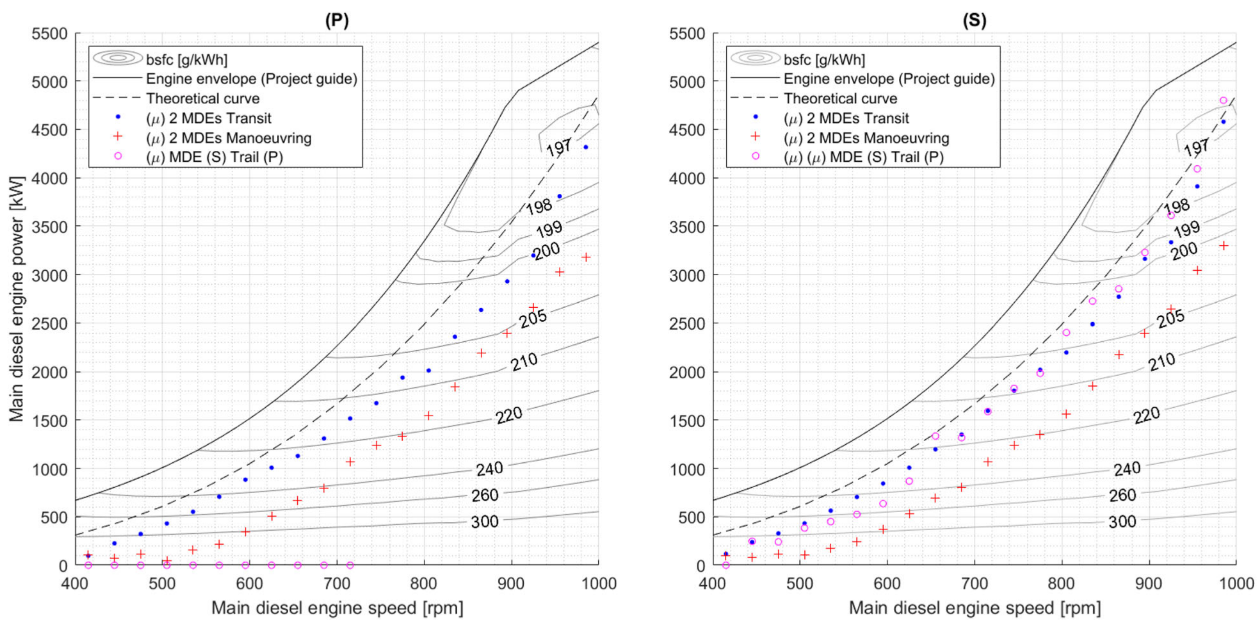


Figure 11. Working points of port (P) and starboard (S) main diesel engines, on 1 MDE trailing and 2 MDEs transit and manoeuvring modes.

4.3.2. Energy effectiveness on different operational modes

Figure 13 presents the two-dimensional distribution of vessel energy effectiveness indicator and the corresponding standard deviation curves. We observe that the effect of the non-uniformly distributed virtual shaft speed settings seen in Figure 6 is also visible in this figure, and that standard deviation varies between 15 kg/mile below 10 knots, and 10 kg/mile above 10 knots. This corresponds to 30% and 15% of mean value respectively, and it clearly suggests that the selection of operational mode and varying operational conditions can significantly affect the resulting energy performance of the vessel within short time windows.

Figure 13 also provides the mean energy effectiveness indicator curves for the four main operational modes. We observe that mean energy effectiveness indicator can vary significantly among the different modes. 2 MDEs transit mode appears to be the most effective mode above 10 knots with the exception of some short speed ranges. 2 MDEs manoeuvring mode, on the other hand, was clearly the less effective mode. 1 MDE trail mode shows a slightly better energy performance than the transit mode above 13 knots and finally, 2 PTIs mode shows a similar energy performance with transit mode below 6.5 knots, and a clearly better performance between 6.5 and 10 knots.

4.3.3. The effect of required thrust on energy effectiveness

The mean energy effectiveness indicator when sailing on 2 PTIs was significantly lower than on all other modes above 6.5 knots, suggesting that electrical propulsion offers significant fuel savings. However, comparing mean total energy efficiency of the system, as discussed in the next section, reveals that transit mode was more efficient. The lower mean energy effectiveness indicator value is caused by the fact that running on the electrical motors was selected while sailing on a

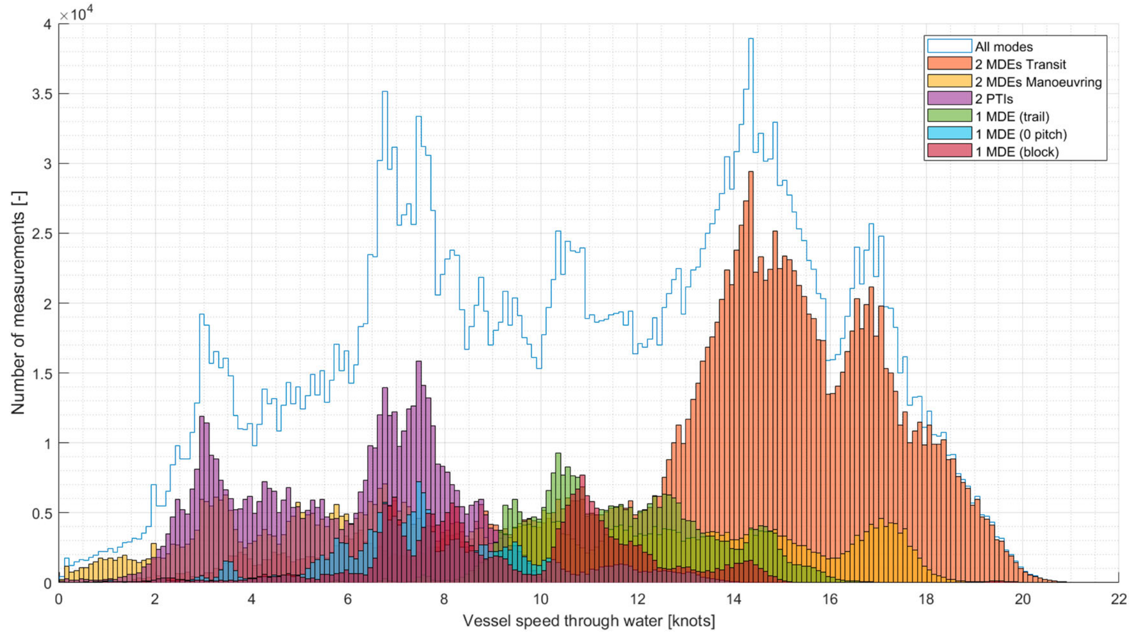


Figure 12. Vessel speed profile of all operational modes.

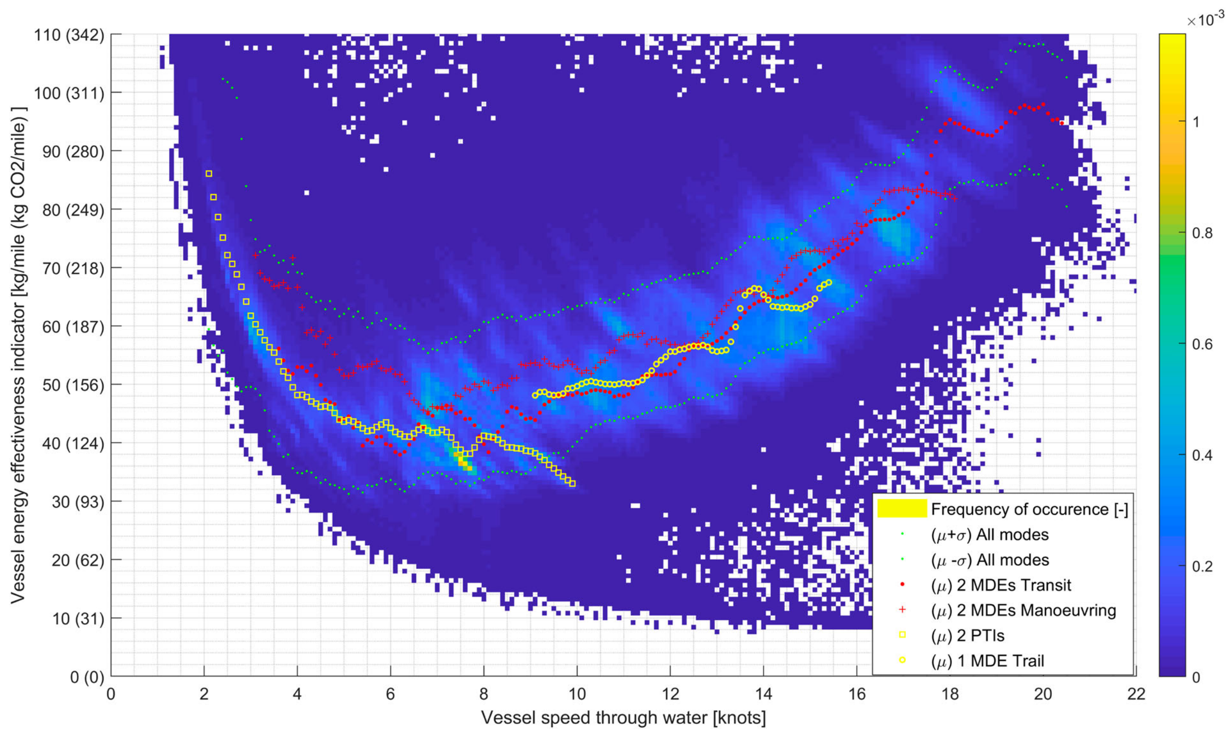


Figure 13. Two-dimensional histogram, mean value and standard deviation of the energy effectiveness indicator, over discretised vessel speed, on the main operational modes.

lighter propeller curve as seen in Figure 14, mainly under favourable weather conditions as supported by the corresponding actual wind histograms in Figure 15.

In order to understand this better, we need to examine the following equation on the relation of energy effectiveness indicator ζ with required propeller thrust T, total energy efficiency η_{tot}, and fuel calorific value h^L. Based on Equations (20) and (19), and furthermore by ignoring the typical weight W as discussed in Section 3.3:

$$\zeta = \frac{\dot{m}_{\text{f,tot}}}{v} = \frac{\dot{m}_{\text{f,tot}} h^L}{Tv} \frac{T}{h^L} = \frac{1}{\eta_{\text{tot}}} \frac{T}{h^L}. \tag{28}$$

This equation suggests that the vessel's energy effectiveness while sailing at a certain speed is directly linked to the highly uncertain thrust requirement. Therefore, mean energy effectiveness indicator curves presented in Figure 13 describe the attained energy performance on the different operational modes, but they correspond to the operational conditions under which those modes were used. Already in Figure 14, we can find mean thrust for the examined modes. It is apparent that mean energy effectiveness curves qualitatively follow the mean thrust curves on each mode.

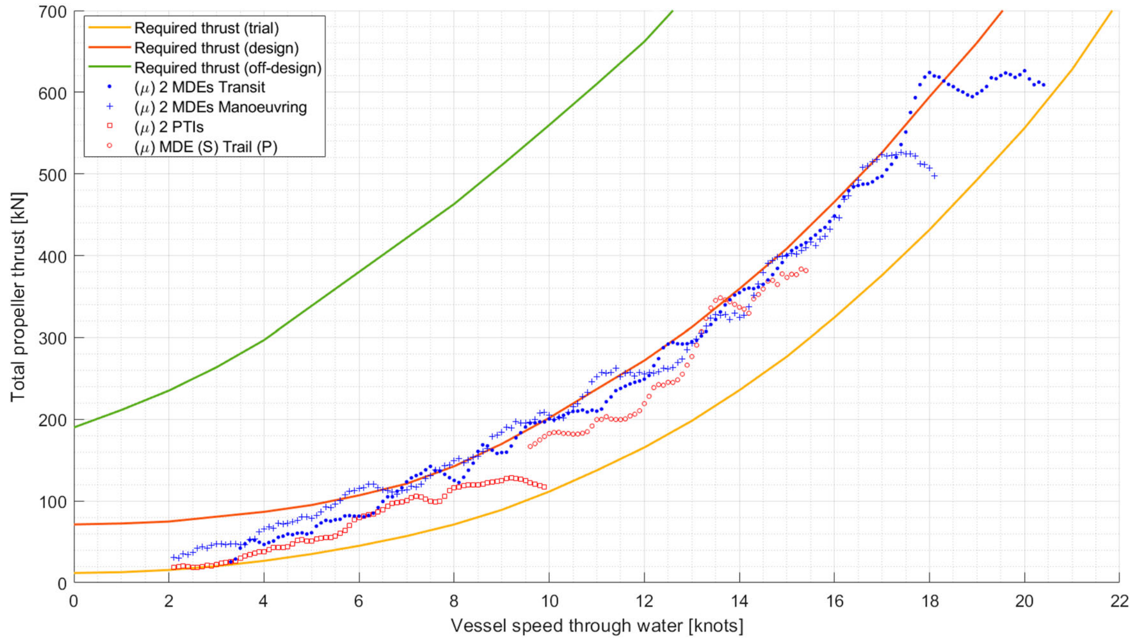


Figure 14. Mean value of the evaluated total propeller thrust on the main operational modes.

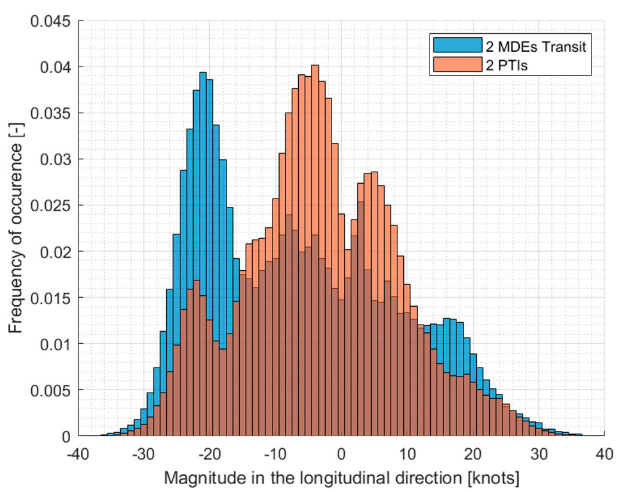


Figure 15. Histograms of actual wind speed in the longitudinal direction, where negative values correspond to head wind. Results bounded between 3.5 and 10 knots of sailing speed.

In order to make a more fair energy performance comparison among different operational modes, we examine the total energy efficiency of the system. Energy efficiency at a whole system and subsystem level is mainly determined by the component working points. While the working points shift due to changing thrust requirements for a given virtual shaft speed setting, the total energy efficiency change is indirect, and of a significantly lower scale than the thrust level change itself.

4.3.4. Energy efficiency on different operational modes

Figure 16 presents the comparison of the mean total system energy efficiency over discretised vessel speed for the different operating modes. This figure shows that the most energy-efficient mode was the 2 MDEs transit one, with a maximum value of mean total energy efficiency equal to 28.5% at 18 knots. Manoeuvring mode was approximately 10–15% less efficient above 7 knots, and 1 MDE trail mode was 10–20% less efficient. Subsystem and component efficiency plots, shown in Figures 17 and 18, indicate the main cause in both cases was the inferior propeller efficiency. Figure 10 suggests that this happens because of the reduced pitch of the manoeuvring mode required to ensure the main engine has more margin to support faster acceleration of the engine and ship, and by the increased propeller speed of the trailing mode in order to provide all thrust by a single shaft. Finally, Figure 11 also confirms that the engine is operated at a conservative operating strategy as stated in Geertsma et al. (2018), as the mean operating points in transit mode are well below the theoretical propeller curve.

4.4. Hybrid propulsion

Hybrid propulsion was selected for the case study patrol vessel in order to prevent main engines fouling and improve energy efficiency at low speed, as diesel engines operating at low power risk fouling due to carbon build-up and show high specific fuel consumption. Figure 16, however, shows that the overall power system energy efficiency of running on the electric motors in 2 PTIs mode was 15–25% worse than on the 2 MDEs transit mode. The subsystem efficiencies, presented in Figure 17 and the component efficiencies in Figure 18 provide insight into the cause of the poor efficiency of the 2 PTIs mode. Figure 17 clearly shows that despite the mean propulsion efficiency on the electrical motors improves compared to the 2 MDEs transit mode by up to 10% above 6 knots, mean power supply efficiency is significantly lower by 15–25%. Nevertheless, if mission requirements allow low-speed transit, it is still advisable to sail near the maximum power of the electrical motors as long as engine fouling is still prevented, since the energy effectiveness in that speed range is low and the amount of fuel consumed is comparably less than at higher speeds, as seen in Figure 9.

First, we examine the components of the power supply subsystem. Mean diesel generators' energy efficiency was between 32 and 35% when running on the electrical motors, compared to 34% on 2 MDEs transit mode. This is already 3% lower than the mean main diesel engine energy efficiency. We also need to consider that an electrical motor's nominal energy efficiency is usually equal to 94–97% (Sofras and Prousalidis 2014). The optimal power allocation of the diesel generators could bring significant energy efficiency gains, as running on three instead of two generators causes the efficiency to drop by 5–10%, as seen in Figure 19. This is also the case, though, when not running on the electrical motors, as the diesel generator efficiency can be improved by 10%, from 36% to 40%, by running one diesel generator instead of two diesel generators as soon as the risk of total electrical failure due to generator failure is acceptable.

On the propulsion subsystem efficiency, gearbox losses on the electrical motors are very high, equal to 7% at 9 knots and 12% at 6 knots, which is 5% less efficient than in transit mode. This is caused by the extra-stage double reduction gearbox needed to reduce the 1800 rpm to 105 rpm. This additional reduction stage could have been prevented by selecting an electric motor with a nominal speed of 450 rpm, with 8 pole pairs instead of 2. If the electric motor had been fitted directly on the shaft, all gearbox losses could have been omitted completely. However, this would have required a significantly larger and more expensive electric motor.

5. Conclusions and future research

The maritime industry must reduce its greenhouse gas emissions in the coming decades. While indices and indicators as the EEDI and EEOI are useful in the energy performance assessment of cargo vessels, they do not provide sufficient insight into the operation of multifunction vessels with diverse operational profiles. In order to provide this insight, operational uncertainties need to be addressed, so as to improve both the design and the use of vessels for the actual operational conditions. In this direction, this paper proposed

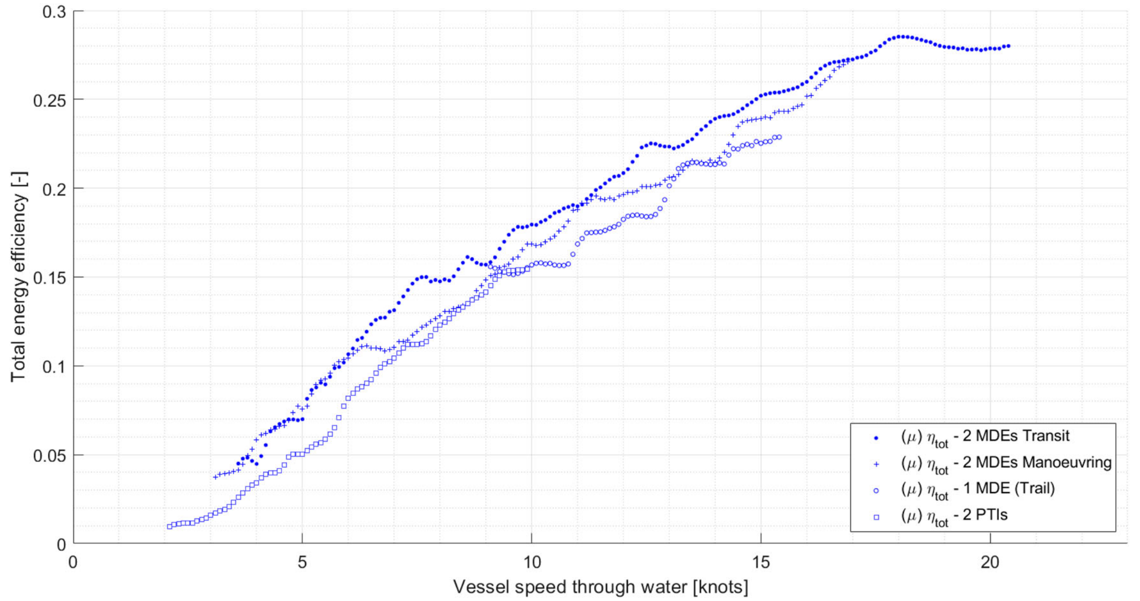


Figure 16. Mean total energy efficiency over discretised vessel speed on the main operational modes.

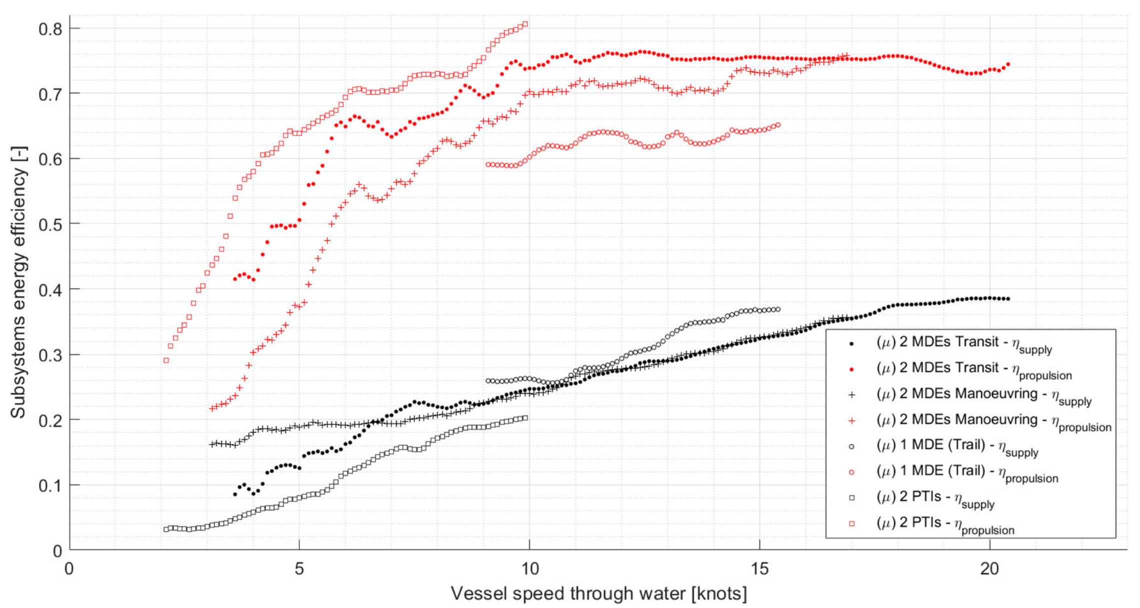
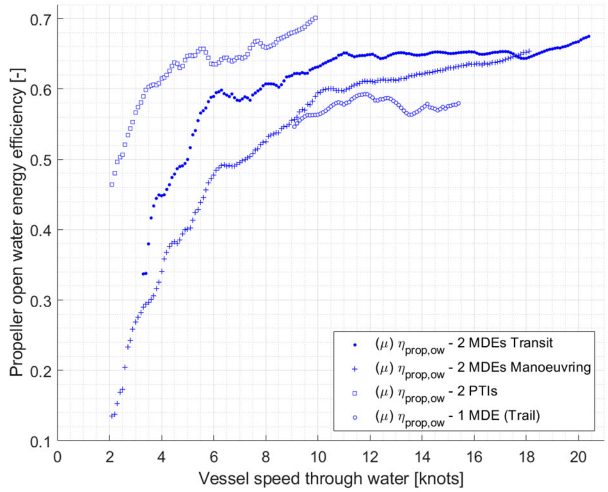
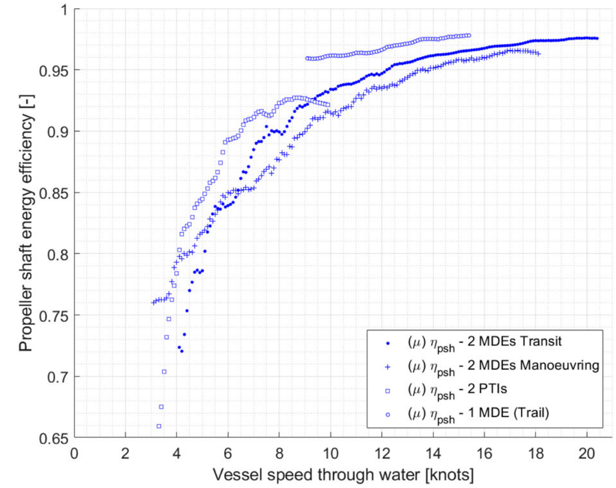


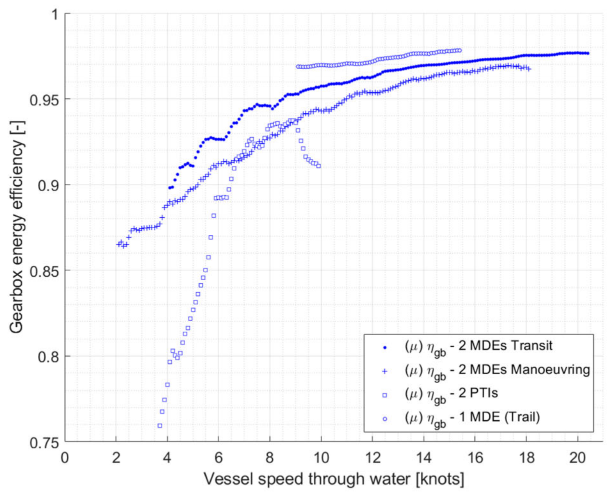
Figure 17. Mean power supply and propulsion energy efficiency on the main operational modes.



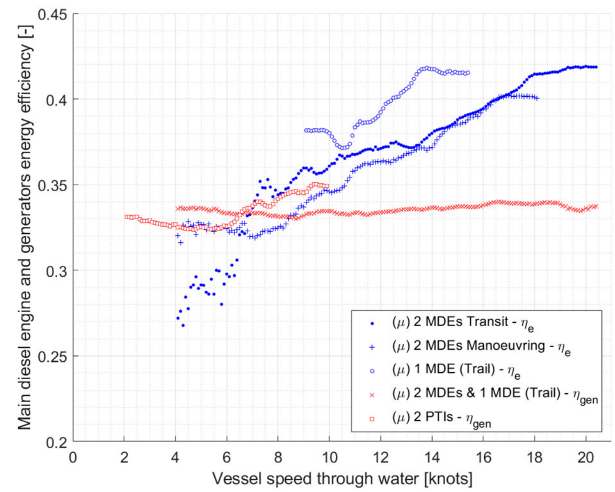
(a)



(b)

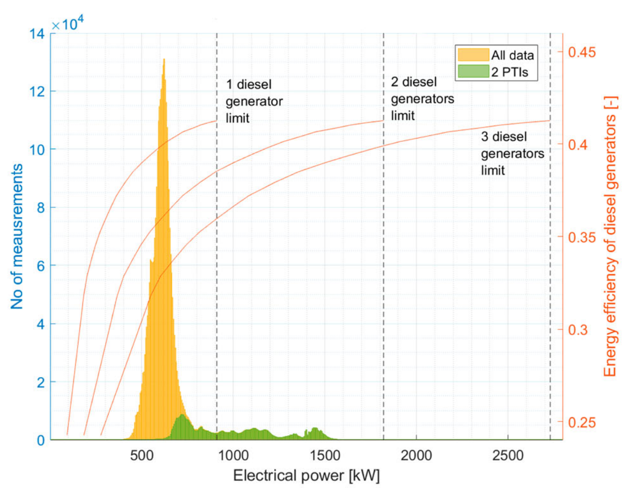


(c)

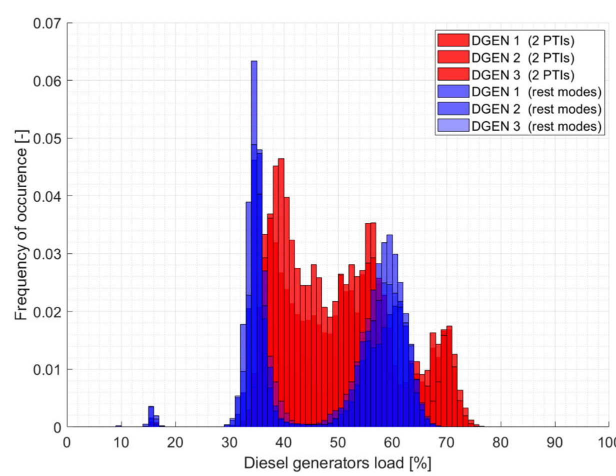


(d)

Figure 18. Component level mean energy efficiencies over discretised vessel speed on the main operational modes.



(a) Combined electrical power supply histogram and energy efficiency of the diesel generators, with and without running on the electrical motors.



(b) Diesel generators load histogram with and without running on the electrical motors.

Figure 19. The difference of electrical propulsion on diesel generators electrical power supply, allocation and energy efficiency. (a) Combined electrical power supply histogram and energy efficiency of the diesel generators, with and without running on the electrical motors and (b) Diesel generators load histogram with and without running on the electrical motors.

a novel operational data-driven methodology that uses logged measurements of a ship's automation system, which was applied on the energy performance and environmental footprint assessment of an ocean patrol vessel belonging to the Royal Netherlands Navy.

Ships equipped with mechanical, electrical and hybrid propulsion can benefit from the following conclusions and recommendations on the methodology:

- Operational conditions such as weather conditions, loading conditions, hull fouling and manoeuvring cause extensive variation of propeller thrust over its mean value at a given vessel speed.
- Mean energy effectiveness indicator for all operational modes combined, as introduced in this paper, is a good measure for the assessment of the achieved energy performance and carbon footprint, and for life cycle fuel consumption and carbon analyses. It provides the operator with insight into the most effective sailing speed, and the cost of sailing faster, but it should not be used to compare the energy performance of different operational modes as it can be distorted due to diverse thrust levels.
- The two-dimensional histogram of discretised energy effectiveness indicator over ship speed, and the corresponding standard deviation curves indicate the uncertainty in the vessel's energy performance caused by discrete operator settings and the varying operational conditions.
- Mean total energy efficiency can be used to compare different operational modes due to its small variation over varying thrust levels.
- System, subsystem and component level mean energy efficiency evaluation can provide the designers with feedback on the design choices over the complete vessel operating profile in actual and uncertain operating conditions.
- Life cycle fuel consumption prediction will most likely be inaccurate without a reliable operational profile prediction.

The proposed methodology provides the following feedback to the operators of the vessel:

- Crew decisions, as the selection of operational mode and the selection of vessel speed, have a similar impact on overall energy performance as design decisions.
- Despite the high energy efficiency of most components at high sailing speed, the vessel consumes less fuel per mile in the range of 30–40% of nominal speed.
- Mean energy effectiveness indicator change for a 1 knot speed change is a good advisor for sailing speed selection.
- The operators appear to have a strong preference for certain discrete speed settings.
- While using electrical propulsion can be less efficient than mechanical propulsion, it can prevent fouling of the diesel engines at low loads. Therefore, for long transits at low speeds, running on the electrical motors is still advisable. Similarly, if speeds above the motors maximum speed are required, sailing on one engine can also reduce maintenance, if the one-shaft reduced manoeuvrability is acceptable.

The proposed methodology provides the following feedback to the designers of the vessel:

- Reducing the electrical motors speed with two reduction stages leads to significant gearbox losses. Fuel savings can be achieved by reducing the speed of the motors, thus the number of reduction stages, if the increased size of the motors is acceptable, and by optimally selecting the number and size of the diesel generators.
- While designers often consider gearbox and shaft losses insignificant, losses at part load are significant and can impact design choices.
- The effect of part load component losses causes total energy efficiency of the system to drop by almost 50% at half vessel speed compared to the nominal speed. Therefore, the use of numerous design points in order to reduce the fuel use and CO_2 emissions of vessels is recommended.

Future work could focus on a number of aspects to be investigated. First, in order to draw safer conclusions on the energy performance of different operational modes, we recommend the use of first-principle models in examining all options under the same operational conditions. Moreover, the application of this methodology on a dataset that includes propeller thrust and torque, and main diesel engine torque sensor readings would make it possible to examine main diesel engine energy efficiency degradation, and propeller and hull fouling. Finally, while mean energy effectiveness provides useful insight for general trends for journey planning, route optimisation algorithms require fuel consumption prediction for the specific conditions the vessel is sailing in. The data analysis proposed in this work is not applicable for this type of analysis. Either first-principle models, or machine learning algorithms would be required to identify the effect of specific operational conditions. However, the enriched dataset proposed in this work can be used by such machine learning algorithms.

The proposed methodology, using operational data from continuous monitoring, provides insight into the impact of operator and design choices for ships, and it allows the better assessment of technical and operational measures. For the case study, a 2 knots increase of the sailing speed between 8 and 14 knots causes a 14% increase of the CO_2 emissions, and a 27% increase above 14 knots. Similarly, an improved design including better auxiliary power allocation and the use of less or no gearbox reduction stages can additionally save approximately 15 to 20% on CO_2 emissions, thus mitigating the environmental impact of ship operations.

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