The influence of propulsion system design on the carbon footprint of different marine fuels

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Abstract

Rising environmental awareness and stricter environmental regulations have increased the interest in new fuels and energy efficiency measures in the shipping industry. Different fuels have different physical and chemical properties that affect the performance of internal combustion engines, e.g. the efficiency, the exhaust gas emissions, and the potential for energy recovery. This has an impact on the potential propulsion efficiency as well as on the life cycle environmental performance. The aim of this study is therefore twofold. First, to assess the potential for optimising the energy use of the propulsion system dependent on fuel choice and second, to assess the overall life cycle global warming potential of the optimised systems. Three fuels are compared, heavy fuel oil (HFO), marine gas oil (MGO), and liquefied natural gas (LNG), in combination with two exhaust gas cleaning technologies, scrubbers and selective catalytic reduction (SCR) units. Data from one year of actual operation with a product tanker are used as a base for the optimization. The results show that the solution with the lowest fuel consumption and carbon footprint is a two-stroke engine with waste heat recovery (WHR) powered by LNG. The synthesis of an optimization procedure for the propulsion system and an LCA approach leads to very interesting results. The different carbon content of different fuels, together with methane slip, leads to a better estimation to the carbon footprint of different propulsion systems. On the other hand, a better insight of the differences between different propulsion arrangements allows performing a more accurate comparison between different fuels. The potential for WHR has a particularly relevant influence on the final result.

Keywords: Propulsion system optimization, shipping, carbon footprint, marine fuels

1. Introduction

The shipping sector is going to face, in the coming years, a number of decisive challenges, which are expected to modify ship design as it has not happened in the last decades. Rising bunker prices and low freight rates demand for increasing fuel efficiency; rising global warming awareness is starting to also affect the shipping sector, which despite its high transportation efficiency has become a significant contributor of greenhouse gases (Buhaug et al., 2009); finally, new environmental regulations, mainly related to the emissions of sulphur and nitrogen oxides (IMO, 2013a), will add complexity to the design and operation of merchant vessels.

1.1 Background

In the preliminary phase of ship design, several different choices have to be made. In particular, decisions connected to the propulsion system will strongly affect the carbon footprint of the ship, and it is therefore of primary importance not to underestimate this phase. The selection of the fuel, the type of engine, and the propulsion arrangement should be performed with maximum care.

The use of computer simulations for the identification of optimum designs has a long history of application in several fields of knowledge, not last that of engineering. In naval architecture, applications of computer models for energy systems can be dated as back as 1984 (DeTolla and Fleming, 1984), while the work from Dimopoulos et al. (2011) is just a more recent example of optimization procedures applied to ship propulsion systems. However, two aspects are very seldom treated in such scientific publications: the accounting of the operational profile, and the selection of the prime mover.

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As stressed by Motley et al., traditionally propulsion systems are designed to optimize performance at a single or few design points (Motley et al., 2012), while the importance of taking the whole operational profile into account was already highlighted by Dupuis and Neilson (1997). Only few examples of different approach are available in scientific literature; Dimopoulos et al. propose the optimization of a combined cycle for marine applications, subdividing ship operations in four well-defined conditions (Dimopoulos et al., 2011); Doulgeris et al. propose the optimization of a propulsion system considering a reference journey, with varying environmental conditions (Doulgeris et al., 2012); Sciberras and Norman, in their work about multi-objective optimization of hybrid propulsion systems refer to the use of extensive data on the operational profile; Motley et al. (2012) also propose a tentative for operational lifetime optimization of a propulsion system, focusing on propeller design.
In the same line, the choice of the prime mover is often left outside of the scope of the work (Dimopoulos et al., 2011, Motley et al., 2012); Doulgeris et al. propose the choice between two alternative gas turbines ((Doulgeris et al., 2012); Sciberras and Norman, instead, use an extensive component database (Sciberras and Norman, 2012); this latter method is applied in the present study.

From the technical point of view, when compared to traditional design practices, two new subjects are today on the agenda for addressing fuel consumption and environmental concerns: fuel choice and waste heat recovery (WHR) systems installation.

As a consequence of new environmental regulations and high fuel prices, the choice of heavy fuel oil (HFO) as ship fuel is not anymore to be given for granted. Emission Control Area (ECA) emission limits can be met either with additional machinery on board (scrubbers, catalysts), or by employing a different fuel, such as marine gas oil (MGO), for compliance with SO_X emissions, or liquefied natural gas (LNG), for compliance with both SO_X and NO_X emissions.

On the other hand, WHR systems are getting largely on the agenda of shipyards and naval architects for the design of new ships; several installations can already be observed on-board existing vessels, and there are expectations for the number to grow rapidly in the future. WHR is a well-known technology which is extensively employed in land-based applications and it allows significant improvements in the efficiency of Diesel engines with using a proven technology and having a rather short payback time(Dimopoulos et al., 2011). It should be noted, however, that WHR systems do not come without any drawback. Lowering exhaust gas outlet temperature can lead to condensation of particles and sulphuric acids on the heat exchangers, thus leading to corrosion. Additional space and weight for the exhaust boiler, turbine, and condenser need to be allocated. Furthermore, the interaction of WHR systems with abatement technologies can lead to complex configurations. The implications of these aspects in the modelling will be discussed in sections 2.1 and 2.2.

The evaluation of different design alternatives is often performed on the basis of energetic or economic principles. However, it is in the beliefs of the authors that environmental impact should be a major parameter to take into account in order to compare design alternatives, especially when the use of different fuels involves diversity both in direct and indirect carbon emissions. In order to evaluate the environmental performance of possible marine fuels life cycle assessment (LCA) can be used. LCA is a method where the environmental performance of products or services throughout the life cycle of the product or service is assessed, ideally including all processes in the life cycle from raw material acquisition to end-of-life disposal.

Several LCAs of marine fuels have been published previously (Corbett and Winebrake, 2008, Winebrake et al., 2007, Bengtsson et al., 2011, Bengtsson et al., 2012, Bengtsson et al., 2013). Corbett and Winebrake (2008) and Winebrake et al. (2007) considered a specific trip with different engine load for different parts of the trip, while Bengtsson et al. (2011, 2013) only considered operation at sea with 85% engine load. Furthermore, Bengtsson et al. (2012) considered the energy use during one year of operation. The engine efficiency was assumed to be the same independently on fuel used in all studies. Nor did any of these studies try to optimize the propulsion system with regard to the fuel. If one fuel has a larger potential for gaining higher propulsion system efficiency than the others, this could have an impact on its environmental performance and should ideally be considered in an LCA.

1.2 Aim

The aim of this paper is twofold. From one perspective, a procedure is proposed for the optimization of the choice of the propulsion system with regard to energy efficiency, taking into account the environmental constraints, and with respect to the choice of fuel, engine type, and possible application of WHR systems. To add one more dimension to the work the overall life cycle global warming potential (GWP) of the optimised systems is compared using an LCA approach, i.e. the carbon footprint.

2. Method

The method here proposed for propulsion system optimization and GWP assessment is supposed to be applicable to ships of any kind and size. However, it will be presented applied to a specific case-study ship, as to make it easier to show its principles and potential. The case study of a product tanker with a deadweight of 45 000 tons will be used. In order to apply the propulsion system design optimization based on real operational data instead of a fixed design point, measured data from one year of operations of a similar ship were used in order to represent the expected ship behaviour.

Data on propulsion and auxiliary power needs in kW are available. The inclusion of propeller design in the optimization process would involve additional complexity, and is left for future studies. The implications of the use of different propeller types and diameters, as well as the complex issues of engine-propeller coupling will therefore not be considered here. The use of a controllable pitch propeller, associated with a gearbox and a shaft generator for auxiliary power generation is assumed in every case, even if this corresponds to an important limitation in the process. The main engine load used in the calculations is presented in Figure 1. Three main operational patterns can be identified: high-load operation (peak at 90% load), when sailing at maximum speed, low-load operation (peak at 55% load), when sailing at economical speed, and port operations (peak at 20% load), when unloading the cargo

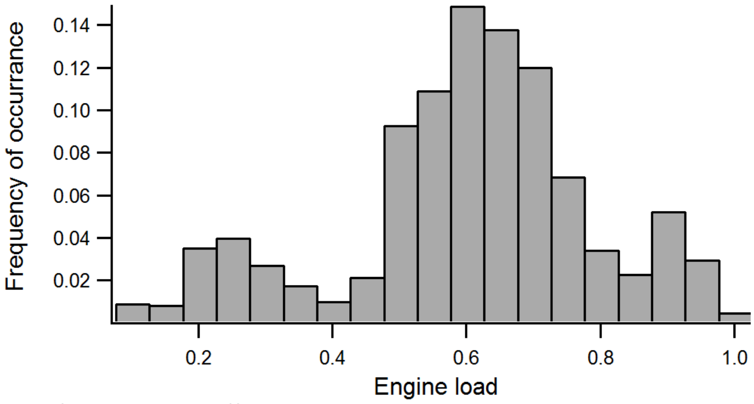

Figure 1. Frequency of occurrence at different engine loads

2.1 Environmental implications

The ship is supposed to to sail into ECA areas. Hence, the chosen design must be able to fulfil ECA areas requirements, i.e. maximum of 0.1% sulphur in the fuel starting from 1st of January 2015 and Tier III NO_X requirements for new buildings starting from 1st of January 2016.[†]

Sulphur emission limits require additional technical arrangements depending on the fuel choice. MGO and LNG have sulphur content below the level required in ECAs. HFO, however, has much higher sulphur content in the fuel (average 2.51 wt. % in 2012 (IMO, 2013b)) that has to be taken care of. The use of a scrubber is assumed in this case, which allows for even high sulphur heavy fuels to respect ECA limits. The electricity needed for pumps and the backpressure imposed on the engine are

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[†] This regulation is under review by the International Maritime Organization (IMO).

estimated to generate a fuel penalty between 1-3% of the engine capacity (Kjølholt et al., 2012). A 2% fuel penalty is added for scrubbers in this study.

Limitations on NO_X emissions require the installation of a SCR unit, apart from the case of 4-stroke LNG powered engines. While little literature is published on the influence of SCRs on engine performance, manufacturers often claim the absence of any fuel penalty (Hagström, 2013); no increased fuel consumption connected to the use of SCRs for NO_X emissions reduction is therefore considered in this study. Furthermore, the effect on exhaust gas temperature is considered to be negligible. The carbon footprint implications of SCRs (direct CO_2 emissions and the GHG impact of urea production and transportation) will be further explored in section 2.4.

2.2 Propulsion system optimization

This paper's first aim is that of describing a methodology to optimize the design of a propulsion system in the early stages of the design. A number of different variable design choices are proposed and analysed separately.

The design choices concern:

1. The number and type of engines: starting from the experience of today existing installation, two possible arrangements were selected:
    - One 2-stroke engine
    - One or two 4-stroke engines
2. The availability of a waste heat recovery system
3. The primary fuel used for propulsion:
    - Heavy fuel oil (HFO)
    - Marine gas oil (MGO)
    - Liquefied natural gas (LNG)

The combination of all the three possible design variables generates 12 possible cases. However, the case of 2-stroke engine, HFO fuelled, equipped with WHR system is not considered because of the technical difficulties in providing the good combination of high temperatures and sulphur concentration in the exhaust required by SCR operations (Magnusson et al., 2012). This leaves a total of 11 different cases to be separately optimized and compared.

The authors have gathered a large dataset from the documentation of the main manufacturers active on the market of Diesel engines for marine propulsion. Data from each engine referred to engine power, efficiency, and exhaust gas properties (temperature and mass flow) for a number of operational points. For 2-stroke engines, data was available for a large number of operative points; hence, spline curves were deemed the most suitable regression technique. For 4-stroke engines data were available only for 3-5 operative points, and second degree polynomial regressions were used instead. For all types of engines the extrapolation of engine performances outside of the original load range was performed using a linear approximation, in order to avoid numerical "explosion" of efficiencies, temperatures, and flows, particularly at very low loads. Efficiency for all engines was corrected in order to account for the typical 5% tolerance allowed under ISO conditions; furthermore, ISO corrections for the addition of engine-driven pumps and for more realistic ambient conditions were applied.

The range of total installed power was set between 7500 and 10000 kW, where the original installed power was equal to 7700 kW. This limited the amount of possible propulsion trains to:

- 18 possibilities for 2-stroke engines
- 14 possibilities for 2-stroke dual fuel engines
- 143 possibilities for 4-stroke engines
- 8 possibilities for 4-stroke dual fuel engines

The relatively low number of total runs (183 runs) allowed testing all possible configurations, therefore avoiding any numerical uncertainty in the results. The computational time for the overall evaluation process is 30 seconds on an Intel(R) Core(TM) i7-2620M CPU at 2.7 GHz processor.

The WHR system is accounted for as a net, free contribution to on-board power production. Exhaust gas temperature and flow are interpolated as a function of load for each engine starting from available data, thus allowing calculating the energy content in the exhaust, which is considered in this work to be the input to the WHR system. Despite the existence of several proposals for WHR systems also harvesting other sources of waste heat, such as charge air cooling (Teng et al., 2007), only the exhaust will be considered in this study.

In order to account for variations in energy quality connected to exhaust temperature, the concepts of exergy is used. Exhaust exergy flows are evaluated, and the power available from WHR system is finally calculated assuming a fixed value for the recovery cycle's exergy efficiency. This approach allows making an assumption of how much the system approaches the ideal, which can be considered a constant for all propulsion system scenarios (Dincer and Rosen, 2013). Values up to 60% can be reached by optimized ORCs (Larsen et al., 2013). However, for the present study, a more traditional single pressure steam based cycle is assumed, as it represents more closely the state-of-the-art in the shipping industry. A reference value of 40% exergy efficiency, consistent with the design proposed by Theotokatos and Livanos (2013), will be used. The implications of using a WHR system in the design are strongly connected to both the choice of the prime mover (2-stroke or 4-stroke engines) and of the fuel.

The implications of fuel choice are mostly related to the environmental impact of the propulsion system, and in particular with its compliance to regulations on the emissions of NO_X and SO_X. Fuel choice also has a strong influence on the efficiency of the propulsion system when the installation of a WHR system is taken into account. A non-negligible amount of sulphur is contained in HFO and MGO. For this reason, sulphur oxides and, as a consequence, sulphuric acid will still be generated after the combustion process. In order to prevent sulphuric acid condensation on the heat exchangers and on the walls of the funnel exhaust gas temperature is not allowed to drop below 150 °C. This limit can be discarded when LNG is used as fuel, as it usually contains less than 10ppm sulphur by mass. The handling of high-viscosity HFO also adds to an additional heat requirement, which was assumed equal to 300 kW regardless the load of the engine, and needs to be produced using exhaust gas heat.

2.3 Analysis of the GHG potential of the optimized designs: an LCA approach

It is important to consider the whole life cycle when comparing the carbon footprint of the optimised designs. Carbon footprint is a limited life cycle assessment considering only the emissions of greenhouse gases in the life cycle (Weidema et al., 2008). The carbon footprint of the optimised designs will be compared by calculating the global warming potential at a 100 year time perspective (GWP), considering emissions of CO_2, CH_4 (1 g CH_4=25 g CO_2-equvivalent) and N_2O (1 g N_2O=298 g CO_2-equivalent) (IPCC, 2007). The whole fuel life cycle is considered starting from raw material acquisition, i.e. crude oil or natural gas, followed by fuel production, distribution and finally combustion in the marine engines. However, the manufacturing, maintenance and scrapping of the vessel is not included. Nor is the manufacturing of the exhaust abatement technologies. The greenhouse emissions and energy use during the manufacturing of the ship has been shown to be very low, less than 3%, when considering the life cycle of the vessel according to Johnsen and Magerholm-Fet (1998) and Walsh and Bows (2011).

Data for the raw material acquisition, fuel production and fuel distribution for the fuels are from Bengtsson et al. (2011). These data are representative for shipping in the northern part of Europe. Two distribution alternatives for LNG are included in Bengtsson et al. (2011), i.e. from the North Sea or from Qatar. Data for natural gas transported from the North Sea is considered in this comparison.

Ammonia is used as a reducing agent in the SCR, normally supplied by a water solution of urea. The data for urea production and distribution are taken from Andersson and Winnes (2011). The emission of CO_2 from the use of urea is included in the data for production of urea (Davis and Haglund, 1999). The estimates for the needed amount of urea is calculated based on data for the NO_X emissions from existing engines (Bäckström, 2010, NTM, 2008) and the amount of urea needed to reduce the NO_X emissions to the Tier III level Is calculated based on the assumption that in order to reduce the NO_X emissions with 2 moles, 1 mole of urea needs to be added to the SCR unit.

The CO_2 emissions from the fuel combustion are calculated from the carbon content in the fuel assuming that 99.5% of the fuel forms carbon dioxide. Fuel properties for MGO and HFO are average data reported in scientific journals (Fridell et al., 2008, Cooper, 2003, Cooper, 2005, Winnes and Fridell, 2009, Winnes and Fridell, 2010), while the fuel properties for Norwegian LNG are from

Edwards et al. (2011). The emissions of methane are taken from NTM (2008) for MGO and HFO (both for 4-stroke and 2-stroke engines), from Bäckström (2010) for 2-stroke LNG engines, and from Wärtsilä published by Bengtsson et al. (2011) and from Nielsen and Stenersen (2010) for 4-stroke LNG engines . The methane emissions from the dual fuel engines are uncertain and very high emissions, i.e. averaging 8 wt. % of the fuel, is reported for the first generation of 4-stroke dual fuel engines (Nielsen and Stenersen, 2010). A 4 wt. % methane slip for the 4-stroke dual fuel engine is considered as a base in the calculations. The emissions of nitrous oxide for the existing engines are taken from Cooper and Gustafsson (2004). Information regarding emissions of nitrous oxide from the gas engines has not been found. The data used is presented in Table 1.

Table 1. Data used for the carbon footprint calculations.

	HFO (1 MJ)	**MGO (1 MJ)**	**LNG (1 MJ)**	**Urea (1 g)**
Well-to-tank				
Primary energy use (MJ)	1.09	1.16	1.1	0.03
Emissions of CO_2 (g)	6.68[a]	7.02[b]	6.97	1.99
Emissions of CH_4 (g)	0.073	0.078	0.046	0.0021
Emissions of N_2O (g)	0.0002	0.0002	0.0036	-
Tank-to-propeller				
Urea consumption (2-stroke) (g)	1.19	1.10	1.06	-
Urea consumption (4-stroke) (g)	0.835	0.835	0	-
Emissions of CO_2 (g)	77.2	73.1	54.4	-
Emissions of CH_4 (2-stroke) (g)	0.000756	0.000744	0.04609	-
Emissions of CH_4 (4-stroke) (g)	0.000463	0.000465	0.816[c]	-
Emissions of N_2O (2-stroke) (g)	0.00388	0.0039	-	-
Emissions of N_2O (4-stroke) (g)	0.00352	0.00352	-	-

[a] The open-loop sea water scrubbers discharge the scrubber water in the open sea, thereby indirectly releasing CO_2 to the atmosphere. Approximately 2 moles of CO_2 is formed for every mole of SO_2 released. This would increase the CO_2 emissions from use of scrubbers with approximately 1.5 g/MJ HFO combusted and is not included in the LCA. [b] Increased energy use in the refineries for producing MGO after 2015 is not included in Bengtsson et al. (2011). However, the CO_2 emissions are estimated to increase with approximately 7 g/MJ MGO based on Avis and Birch (2009), when allocating the total increase in CO_2 to the production of MGO. [b] This parameter have been varied between 0.28 g/MJ and 1.63 g/MJ representing between 1.4 and 8 wt. % methane slip.

3. Results

Here follow the results for the propulsion system optimization as well as the carbon footprint calculations.

3.1 Propulsion systems

A total of 183 design alternatives were evaluated and compared. In order to validate the results, the modelled consumption was tested versus the measured one using the data corresponding to the arrangement of the original ship. This showed reasonable accuracy, as calculated consumption differs from measured consumption by 5%, which could be explained by engine wear and non-optimal operating conditions. Moreover, measurement accuracy derived from fuel meter and shaft power meter is equal to around 5%, meaning that the two results are not significantly different.

Results for the total fuel consumption over one year of operation (valid only for the main engines) are shown in Figure 2, displayed as TJ/year. Values are given for each fuel choice, and for each type of engine selected. Two values are showed for each combination, referring to the case with and without the installation of WHR systems, apart from the case of 2-stroke propulsion arrangement with HFO as a fuel, where technical limitations do not allow the application of WHR. The horizontal red line refers to the original arrangement for the selected ship (hereafter referred to as “reference case”). For each scenario “range bars” are also displayed, representing the average, maximum and minimum results for each possible arrangement. It should be noted however that only the best point was used for the further analysis.

The best selected arrangement for all 2-stroke cases coincided with the most efficient engine at design point, as is also showed in Table 2. In the case of 4-stroke arrangements, instead, a father-and-son arrangement proved to be the best efficient in all cases, with a large, efficient engine (rated power of 7200 kW in HFO and MGO cases, 5850 kW in the LNG case) supported by a smaller engine (1020 kW and 2700 kW) at low and peak loads. The benefit of operating in off-design conditions for shorter time in the case of 4-stroke, dual fuel engines is justified by the lower efficiency of these engines at low-load operations, as they operate according to a Otto-cycle (Aesoy et al., 2011).

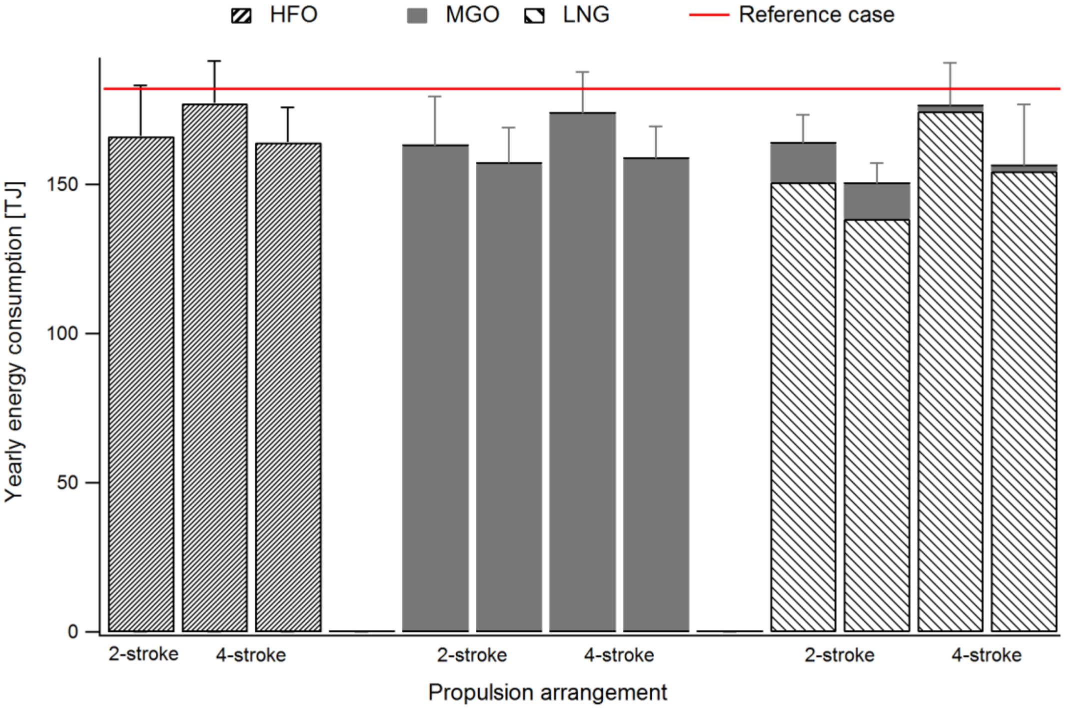

Figure 2. Energy consumption from one year of operation for the presented cases.

One of the aims of this paper was that of estimating the relevance of different details related to the design of the propulsion system when evaluating the carbon footprint of the selected ship, both in absolute and relative terms for comparison between fuels and arrangements. In order to compare the influence of the different aspects, Table 2 shows, for each case, the modifications observable in the yearly energy consumption when adding more detail to the modelling, where:

- Level 1: Constant engine load, constant engine efficiency assumed based on existing data (engine load fixed at 75% according to EEDI calculation; engine efficiency assumed from Buhaug et al. (2009) equal to 170 g/kWh for 2-stroke engines and 190 g/kWh for 4-stroke engines).
- Level 2: Real operational load, constant engine efficiency based on the most efficient arrangement at design conditions.
- Level 3: Real operational load, load-dependent engine efficiency based on the most efficient arrangement at design conditions.
- Level 4: Real operational load, load-dependent engine efficiency based on the most efficient arrangement taking the operational cycle into account.
- Level 5: Real operational load, load-dependent engine efficiency based on the most efficient arrangement taking the operational cycle into account, with WHR.

Table 2. Energy consumption in TJ for one year of operation and for different levels of modeling detail.

	2-stroke engine			**4-stroke engine**		
	HFO	**MGO**	**LNG**	**HFO**	**MGO**	**LNG**
Level 1		223			249	
Level 2	151(-33%)	148(-34%)	156(-30%)	168(-33%)	165(-34%)	164(-34%)
Level 3	166(9.9%)	163(10.1%)	164(5.1%)	178(6.0%)	175(6.1%)	179(9.1%)
Level 4	166(0.00%)	163(0.00%)	164(0.00%)	177(-0.56%)	174(-0.57%)	176(-1.7%)
Level 5	162(-2.4%)	157(-3.7%)	150(-8.0%)	164(-7.3%)	159(-8.6%)	156(-11%)

3.2 Carbon footprint

The carbon footprints of the optimised systems are presented in Figure 2. The case with the overall lowest carbon footprint is LNG with 2-stroke engines combined with WHR. The 4-stroke dual fuel engines have a significant higher carbon footprint caused by a large methane slip from the engine during combustion. The 4-stroke dual fuel engine cases vary from having the third and fourth lowest carbon footprint to the highest dependent on the estimates of the methane slip.

The largest contribution to the carbon footprint originates from the combustion of fuels in the marine engines (between 84-88%). Acquisition of raw material, fuel production and distribution stands for between 10-13% while urea production and transportation stands for between 0-3% of the carbon footprint.

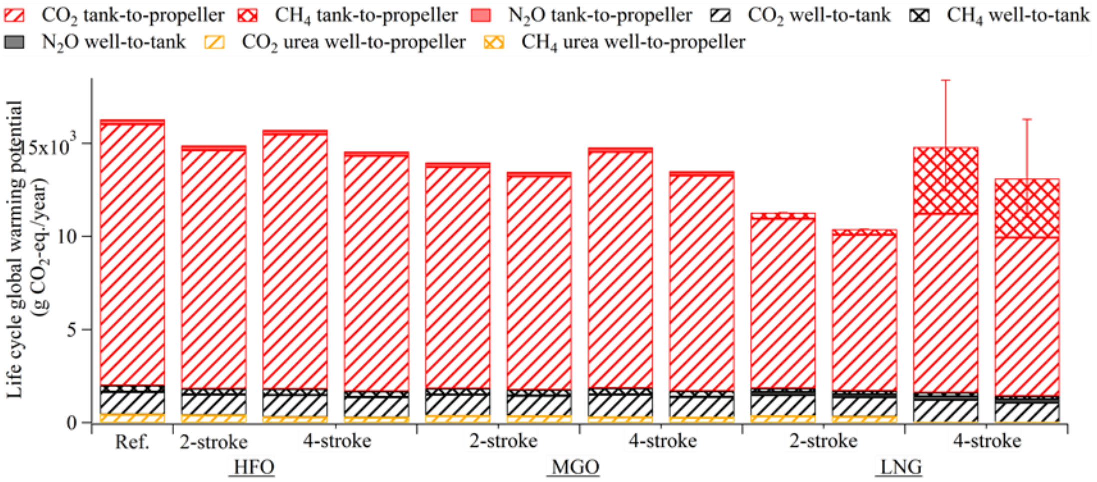

Figure 3. The carbon footprint of the optimised systems divided on the contributing greenhouse gases and the different phases in the life cycle. The range for the 4-stroke dual fuel engines represents the difference between a methane slip of 1.4 and 8 wt. % during combustion of LNG. Results with and without WHR are presented for all alternative except for the alternative with HFO and 2-stroke engines. The second bar for each engine arrangement represents the system with WHR.

Table 1Table 3 gives an overview of the result comparing the propulsion system energy use and the carbon footprint for the selected cases compared to the reference case, representing the modelled energy use with today's propulsion system on the product tanker. The propulsion system energy use is reduced by 28% while the carbon footprint is reduced by 36% for the case with a 2-stroke LNG engine with WHR.

Table 3. Comparison of the propulsion energy use and the carbon footprint for the selected cases. The difference compared to the reference case (182 TJ) is presented in parenthesis.

	Propulsion energy use (TJ/year)	**Carbon footprint (tonne CO2-eq./y)**
HFO 2-stroke	166 (91%)	14800 (91%)
HFO 4-stroke	177 (97%)	15700 (97%)
HFO 4-stroke with WHR	164 (90%)	14500 (89%)
MGO 2-stroke	163 (90%)	13900 (86%)
MGO 2-stroke with WHR	157 (86%)	13400 (82%)
MGO 4-stroke	174 (96%)	14700 (90%)
MGO 4-stroke with WHR	159 (87%)	13500 (83%)
LNG 2-stroke	164 (90%)	11300 (70%)
LNG 2-stroke with WHR	150 (82%)	10400 (64%)
LNG 4-stroke	176 (97%)	14800 (91%)
LNG 4-stroke with WHR	156 (86%)	13100 (81%)

4. Discussion

The discussion is divided in three parts discussion on the results, on the method and on potential future work.

4.1 Result discussion

The analysis of Figure 1 shows that 2-stroke dual fuel engines are the most efficient solution from a purely energetic perspective. The 4-stroke engine solution (which is also the current arrangement for the existing ship) is a competitive alternative only when a WHR system is in place, as 4-stroke engines generally feature higher exhaust temperature, when only direct fuel consumption is accounted for. The observation of the results for the carbon footprint, however, has a strong influence on the evaluation. On the one hand, the lower carbon content in the fuel and the very low sulphur content makes 2-stroke LNG-powered solutions even more convenient (carbon footprint is reduced by 36% compared to the reference case when WHR is used). On the other hand, taking the methane slip into account makes the LNG 4-stroke solution much less viable, even if this result is strongly affected by the uncertainty in the data.

The observation of the range bars shows the size of the variation in the results, thus confirming the additional value of implementing a propulsion system optimization algorithm in order to evaluate the overall yearly consumption. The variation between the two extremes of the range varies between 6% and 10% depending on the case, while the standard deviation lies between 1.5% and 3%. The utilization of a complete operational profile for the evaluation of the propulsion arrangement instead of a single operational point only has an influence when a multi-engine arrangement is employed. In fact, for all 4-stroke engine cases, multi-engine solutions prove being the most efficient, regardless the fuel. The advantage compared to the use of the most efficient engine alone is rather small in the HFO and MGO cases (0.7% improvement), but larger in the LNG case (1.7% improvement). The presence of WHR has no influence on the choice of the engine, regardless the case. The small amount of power produced by the WHR system does not justify the choice of an engine with lower efficiency but, for instance, higher exhaust temperature. However, as observable in Figure 1, taking WHR systems into account can significantly decrease the overall consumption (between 2.4% and 6.7%, with the assumed recovery efficiency).

The propulsion system optimization has shown to have a significant impact on the life cycle GWP. The propulsion energy needed spans between 150-177 TJ per year depending on the selected designs. The increased potential for WHR for LNG compared to HFO and MGO is important and should be considered when evaluating the environmental performance of LNG for future marine propulsion. The carbon footprint when using 2-stroke or 4-stoke dual fuel engines was significantly different, showing that the propulsion system should not be neglected when calculating the carbon footprint.

From an engine optimization perspective, this approach provides additional insight about the climate impact of the propulsion system. It is here shown that the energy use and the carbon footprint are not directly proportional, as the carbon content is different between the different fuels and the non-CO_2 emissions contributing to global warming are different dependent on the different propulsion systems, especially in the case of dual fuel engines. From an LCA perspective it is possible to gain insight of the potential for energy efficiency improvement for the different fuels, e.g. the LNG propulsion systems can extract more energy from a WHR system due to the very low sulphur content. We suggest that this approach could contribute to a more complete understanding of the propulsion systems available and their pros and cons. This approach could therefore be used to provide decision support when selecting propulsion systems for new vessels.

4.2 Method discussion

The implications of the results presented in this paper would not be complete without a discussion of the methodology employed in this paper, and specifically of the different assumptions that had to be made.

Data for different engines were obtained from publicly available technical documents from different engine manufacturers. Data for 2-stroke engines from MAN were very extensive, with detailed fuel consumption, exhaust mass flow and temperature for 14 different load points. The same cannot be said, unfortunately, for data concerning 4-stroke engines, obtained from Wärtsilä and MaK: in these cases, in fact, data points were available for only 3 to 5 different loads, which involves less accurate approximations in the mathematical regression. For all engines, in addition, the variations generated by the possibility of influencing cylinder loading, valve timing, and turbocharger matching were neglected. The availability of better and more extensive data would definitely improve the quality of the approximation.

The installation of the SCR was also taken into account, with no fuel penalty. There is some controversy on this point, as manufacturers claim no fuel penalty (Hagström, 2013) while some tests have shown the opposite (Subramaniam et al., 2011). Moreover, the presence of an SCR would allow a much more efficiency-driven engine tuning, as Tier II engines normally comply with NO_X emissions regulations by reducing combustion pressures and temperatures and, thus, engine thermodynamic efficiency. No study is known to the authors that could show the effect of the combination of the two different phenomena. Similarly, the approximation employed in this study in order to account for the scrubber power needs is quite strong, and, in presence of more extensive data, could be further improved.

The result of an LCA study depends on the goal and scope of the study and the data used in this paper are specific for operation in the northern part of Europe considering marine transportation in 2015-2020. Ideally, the data used in the LCA should be specific for the region and the time in which the new ship will operate. In this study the geographical operation and time scale are not defined. However, the part of the life cycle that contributes the most to the carbon footprint is the combustion of fuel in the tank-to-propeller phase and this data is specific for the different types of engines used. The second biggest contributor to the carbon footprint is the fuel production phase. This data may vary between different production facilities, but still when considering future operation it can be expected that state-of-the-art production today independent on geographical scope can be representative.

It is highlighted that the methane slip from the dual fuel engines has a significant impact on the carbon footprint. The uncertainty on this value is very high and needs to be verified with actual on-board measurements during operation. The only data available today are from engine manufacturers and a few measurements on vessels operating in Norway (Nielsen and Stenersen, 2010). 2-stoke dual fuel engines are operating according to the diesel process and have a much lower methane slip than the 4-stroke lean burn dual fuel engines included in this analysis. It is also possible to use 4-stroke dual fuel engines operating according to diesel process; this would result in lower methane slip and higher NO_X emissions, which is the case for the 2-stroke LNG engines. Another possibility may also be to use oxidation catalysts in order to reduce the CH_4 emissions. Furthermore, there are no emission factors for nitrous oxides for the dual fuel engines.

4.3 Future work

This study opens for a number of alternatives for future work.

As mentioned in the description of the method employed in this study, leaving the propeller out of the optimization procedure constitutes a very strong approximation, which is hardly justifiable in practical terms. In particular, 2-stroke engines performance would then be even higher, as no gearbox losses are involved in a directly coupled arrangement between engine and propeller. Moreover, engine speed should then be taken into account, as it strongly influences propeller efficiency, and vice versa. As an additional consequence of this simplification, auxiliary needs (though rather limited in the case study taken into account), are assumed to be a part of the main engine load, as the current arrangement is provided with a shaft generator. This is definitely a viable alternative, but accounting of different possible designs for auxiliary power generation would be an improvement to the quality of the results.

The methane emission from the combustion of natural gas in marine engines is shown to have a great impact on the overall result. The methane slip is markedly load-dependent and could potentially be as high as 15 wt. % at low engine loads (Nielsen and Stenersen, 2010). Hence, the availability of load-dependent methane slip emissions would be an additional improvement to the calculation of the greenhouse gas emissions from combustion.

The approach of combining a propulsion system optimization with carbon footprint calculations gives information on two important aspects when selecting the propulsion system in the design of a new ship. It would, however, be possible to combine the engine optimization with a full LCA and not only the carbon footprint and thereby providing information about a number of different environmental impacts.

As have been mentioned before a number of LCA studies on marine fuels have been published and data from these could rather easily be combined with data from engine optimizations. When performing a complete LCA there are more emissions from combustion that could be calculated based one the operational profile of the ship, e.g. nitrogen oxides, carbon monoxide and particles; thus, making the result even more accurate.

When making a decision of which propulsion system to choose there are more parameters that are important to consider then only the energy use and the environmental impacts, e.g. the cost of the system, the reliability and ease to operate, the knowledge about the system and so on. This could, for example, be considered in a multi criteria decision analysis.

5. Conclusions

In this paper we have presented a combination of a design optimization methodology with a carbon footprint analysis which could be used as decision support in the design process for new ships. The most efficient propulsion system was selected for a number of different engine types and fuels, taking into account a real operational pattern, referred to one year of operation of a similar existing ship. This procedure showed to improve the efficiency of the design when 4-stroke engines are employed, especially with LNG as fuel.

The 2-stroke dual fuel engine, equipped with a WHR system, proved to be the arrangement with the lowest carbon footprint. The WHR system proved to significantly improve the overall performance. The 4-stroke dual fuel engine solution, even though showing promising performance from an energy perspective, loses appeal when methane slip is also taken into account. When compared to traditional LCA studies, this work showed the importance of the selection of the propulsion system, as compared to the assumption of a common efficiency for all engines, in particular when off-design performance is taken into account.

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