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Environmental and economic sustainability assessment of emerging cruise ship energy system technologies

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Abstract:

The environmental and the economic impact of ship energy systems is a rising concern for the shipping industry. A number of technologies to improve the sustainability of ship energy systems exists. The majority of previous research on ship energy systems selection focused on the techno-economic performance of one or two components. However, an approach of evaluating simultaneously the environmental and economic performance of the integrated ship energy systems is missing. In this respect, this work aims to identify the most sustainably performing configuration of cruise ship energy systems by quantifying and evaluating the life cycle cost and the CO_2 lifetime gaseous emissions of the integrated ship energy systems. The machinery responsible for the propulsion, electric and thermal power production, as well as emission reduction and energy efficiency is included. The performance of existing and emerging technologies is modelled including fuel cells, carbon capture technology, waste heat recovery systems, as well as propulsion and auxiliary systems with alternative fuels such as LNG. Alternative system configurations of the investigated ship are generated and assessed based on on-board operational data of a cruise ship. A set of dominant solutions is derived by employing a multi-objective evolutionary algorithm and indicative results for the most sustainable configurations are presented. A sensitivity analysis is performed for future fuel prices and technologies capital cost for the year 2030. The derived results from the cruise ship case study indicate that the ship energy systems sustainability can be improved by adopting natural gas dual fuel technologies and fuel cells. In addition, introducing a carbon capture technology and a waste heat recovery in the ship energy systems can improve the carbon footprint.

Keywords:

Cruise ship energy systems, Environmental and economic sustainability, Lifetime CO_2 emissions, Operating data, Emerging technologies, Sensitivity analysis.

1. Introduction

1.1. Background

The economic crisis as well as the regulatory pressures in the recent years have been very challenging for the maritime industry. The International Maritime Organisation (IMO), the main regulatory body for shipping operations highlights the imperative need for more sustainable shipping operations and sets targets for reducing air emissions from vessels to mitigate the adverse impacts on human health and environment. The IMO sets limits on the emissions of NOx (Tier II standards for global waters and Tier III for Emission Control Areas ECA), SOx and particulate matter (PM) from ships [1]. In addition, regulations to reduce the greenhouse gas emissions have been introduced and further pressures are foreseen in the future. On 2013 IMO introduced the first maritime energy efficiency regulation. According to it all new ships have to comply with the Energy Efficiency Design Index (EEDI) [2] and existing ships need to have a specific Ship Energy Efficiency Management Plan (SEEMP) [3]. The EU also adopted a monitoring, reporting and verification system (MRV) for carbon dioxide emissions [4]. In light of the environmental legislation, uncertainties on fuel prices and the fact that bunker fuel prices can account for more than 50-60% of the vessel's operating costs [5], there is a rising concern for ensuring the vessel cost-efficiency.

In order to improve the environmental and economic impact of ship energy systems there is a variety of alternatives with existing and emerging technologies. Natural gas as a fuel for power generation [6] is considered to have an improved environmental and economic performance. Fuel cells for marine application, are gaining great interest due to the ultra-low exhaust gas emissions [7]. A variety of emission reduction technologies exist that reduce the NOx [8], SOx [9] and CO_2 [10] exhaust gas emissions of the engines. Electric energy storage is also discussed as a way in order to improve the ship energy efficiency [11].

1.2. Previous Work

The cruise ship industry is a growing sector and given the high energy demand and complexity of the ship energy systems, the focus on cruise ship energy systems has gained lately great interest. An extensive number of studies were published in the past focusing on specific ship technologies in order to improve the cruise ship energy systems performance.

The installation of gas turbines on cruise ships as prime mover in order to improve the environmental impact and the installation weight was investigated in [12]. In [13] the economic optimisation of a combined gas turbine electric and steam configuration was performed. The economic investigation between two alternative propulsion systems with dual fuel engines or diesel engines of a cruise ship, in order to comply with Tier III regulations was addressed in [14]. Fuel cell technology for marine applications for high complexity energy systems like on cruise ships, was discussed in [15]. In [16] the economic optimisation of the load allocation of a hybrid configuration of a cruise ship was presented. The economic design and operational optimisation of a cruise ship power plant, with diesel engines, waste heat recovery and electric energy storage was performed in [17].The waste heat recovery of the cruise ship engines exhaust gas was also discussed. The thermo-economic analysis of an Organic Rankine cycle was presented in [18] and the simulation of the performance of an Organic Rankine Cycle was discussed in [19].

The majority of previous research focused on the techno-economic performance of one or two components or a specific configuration of a cruise ship. However, an integrated approach of ship energy systems that includes the considerable number of components and their interconnections has not been presented in the relevant literature. In addition, the evaluation of the systems focused mainly on the economic performance, whereas the simultaneous assessment and optimisation of economic and environmental performance of cruise ship energy systems has not been addressed.

1.3. Aim

The aim of this work is to identify the most sustainably performing configuration of cruise ship energy systems by quantifying the life cycle cost and the CO_2 lifetime gaseous emissions of the integrated ship energy systems and evaluating the alternative system configurations' performance. Cruise ship energy systems include the machinery responsible to cover the propulsion, electric and thermal power demand, as well as the emission reduction and energy efficiency technologies. The bi-objective evaluation and optimisation based on both environmental and economic objectives for the integrated, alternative cruise ship energy system configurations is considered one of the contributions of this work. Another novelty of this research is the inclusion and evaluation of emergent technologies, along with the traditional ones, in order to investigate more sustainable cruise ship energy systems configurations.

2. Methodology

A detailed description of the method and the modelling assumptions can be found in previous work of the authors [20].

2.1. Ship energy systems modelling

In this work mathematical models for investigating ship energy systems, including both existing and emerging technologies, were developed, in order to simulate the performance of the systems. Each sub-system performance is modelled separately, while considering the interactions among the sub-systems.

The diesel and dual fuel generators performance equations are derived from regression analysis from manufacturer brochures found on the project guides of Man Diesel & Turbo [21,22] and Wärtsilä [23] with range of nominal power between 3000-20000 kW. According to the manufacturers' project guides, all the engines comply with the Tier II regulations and Wärtsilä dual fuel generators with pre-mixed fuel comply with the Tier III regulations while operating in the gas mode. The specific fuel oil consumption or specific energy consumption, the exhaust gas amount and exhaust gas temperature are represented with second order polynomials. The models are steady state and do not consider the fuel increase on transient conditions. However, the degradation of the engine due to aging is taken into account as an increase of the fuel consumed according to [24,25]. For the cost calculation of the engines, both the tank storage and treatment of the engine fuel is considered. The equations for the generators efficiency and for the part load correction factors, are estimated according to data provided in [26].

The fuel cells performance is modelled according to [27], the efficiency of the reformer, inverter and frequency converter is assumed constant in every load and is considered leading to an overall efficiency of 42% on the AC of the power grid of the ship. The fuel consumption of the thermal boiler is modelled as a function of the saturated steam energy and the boiler efficiency, whereas the part load curve is assumed according to [16].The waste heat recovery system's performance and the total electric energy produced from the generator, are modelled for a single pressure boiler and a turbo-generator according to [26].

The equation representing the urea consumed from the selective catalytic reactor is a function of the amount of NOx emissions reduced and is derived from [28]. The effectiveness of the emission reduction technologies for NOx emissions are derived from [29] and the scrubber is considered to reduce the sulphur content of the fuel in order to comply with the IMO regulations [30].

The carbon capture technology efficiency and the caustic soda amount needed in order to reduce the CO_2 emissions from the exhaust gas of the engine is modelled according to [10]. It is assumed that the carbon capture technology removes around 10% of the CO_2 from the exhaust gas of the engines. The reduction potential of the carbon capture technologies is higher; however a greater reduction has an adverse effect on the ship payload due to the space requirement of the carbon by products and therefore is considered impractical.

2.2. Bi-objective optimisation

The majority of real world problems are represented by multiple objectives, regarding economic, environmental and technical objectives. The selection of ship energy systems is also one of the cases that it is driven by more than one objectives. Reducing the environmental impact of the systems leads to increased cost, thus the problem has multiple, conflicting objectives. Multi-objective evolutionary algorithms (MOEA) for solving problems with multiple objectives, has shown great acceptance in academia as well as the industry in the last decades [31]. In addition, MOEA as well as Pareto optimisation methods, offer the opportunity to the decision maker to come to a decision after examining all the optimum potential solutions, without 'a priori judgment' [32]. The Non-sorting genetic algorithm NSGA-II developed by Deb [33] has been selected in this work. The NSGA-II manages to offer a uniform distribution of the solutions on the Pareto front due to the crowding distance metric and favours solutions that are quite diverse, due the elitist mechanism. It is a method widely used for multi-objective combinatorial optimisation problems as the particular problem presented in this paper.

To quantify, evaluate and minimise the life cycle cost and the lifetime CO_2 gaseous emissions of the cruise ship integrated energy systems the optimisation problem can be summarised as follows:

$$Z = \mathrm{Min}\ [f_1, f_2], \qquad (1)$$

The objective functions are optimised simultaneously and are defined as:

$$f_1 = \mathrm{capex} + \sum_{k=1}^{Y} \frac{\mathrm{opex}_k}{(1+\mathrm{ir})^k}, \qquad (2)$$

$$f_2 = \sum_{k=1}^{Y} E_{CO_2}, \qquad (3)$$

The objective function f_1 minimises the life cycle cost over the vessel lifetime and f_2 minimises the CO_2 lifetime emissions of the ship energy systems.

The optimisation problem is subject to the following constraints:

- Regulatory: environmental and minimum installed power requirements.
- Energy demand: satisfy the power requirements for each operational phase.
- Technical: satisfy the compatibility of technologies and fuel alternatives within a single configuration.

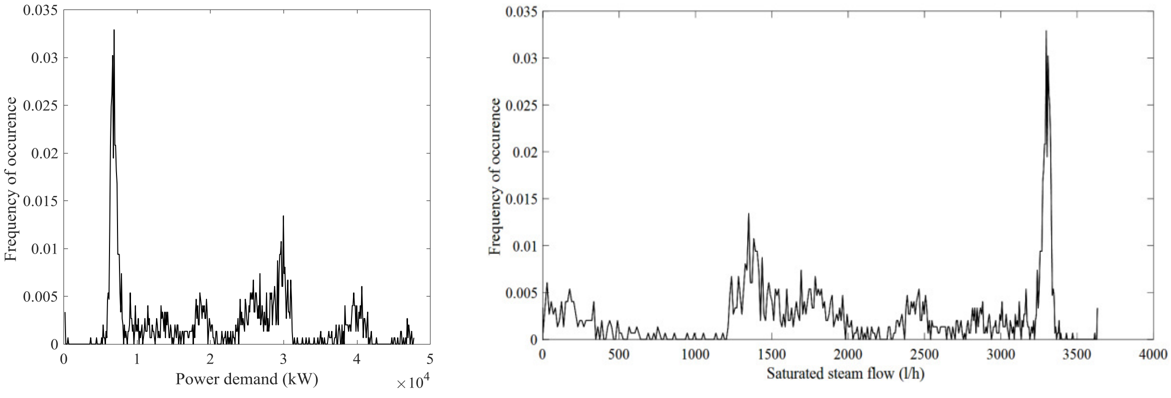
The optimisation decision variables are the:

- type of the main engines
- fuel type of the main engines
- number of the main engines
- nominal power of the main engines
- type of the thermal boilers
- fuel type of the thermal boilers
- existence of a particular emission reduction technology
- existence of a particular energy efficiency technology

3. Case Study

The presented bi-objective optimisation is illustrated through a case study on a cruise ship. Details for the fuel prices and the technologies capital and operational cost factors can be found in [20].

3.1. Inputs



(a)

(b)

Fig. 1. Operational profiles for cruise ship: a) Total propulsion and electric power demand, b) Saturated steam mass flow.

For the selection of ship energy systems, the inclusion of the operational profile is significant. From previous studies [34] it was identified that the cruise ships are mostly operated in lower speeds than the design, leading to underutilisation of the power capacity. For this reason, in this case study real operational profiles, Fig. 1, were used in order to estimate the ship energy systems performance. The profiles were derived from real operational data of a cruise ship and distinct operational phases with specific power requirements and duration, were estimated. The operational phases were used for the evaluation of the energy systems lifetime performance.

It is assumed that the cruise ship operates 10% of its time inside Emission Control Areas and the investigated lifetime of the vessel is 25 years with a 7% of time annually that the ship is non-operational.

The investigated alternative technologies of the specific case study are summarised in Table 1. According to technical constraints, not all the combinations are feasible.

Table 1. List of alternative technologies for the case study

Engine types	diesel[1] dual fuel pre-mixed or gas injected[1] molten carbon fuel cells[2]
Engine fuel type	HFO, LSHFO, MGO NG & MDO pilot fuel Natural Gas (NG)
Thermal boiler type	oil fired gas fired
Thermal boiler fuel type	HFO, LSHFO, MGO NG & MDO pilot fuel
Energy Efficiency Technologies	Waste Heat Recovery system with Turbo-generator (WHR)
Emission reduction technologies	Exhaust Gas Recirculation (EGR) Selective Catalytic Reactor (SCR) Scrubber Carbon Capture System (CC)

3.2. Assumptions

The configuration for the specific case study is considered fully electric. The electric power is distributed to the electric system panels and electric motors drive the ship propellers. This is a very common configuration for a cruise ship, and the power can be provided by several engines. A maximum of two different types of engines are assumed in this case study, because multiple engine types have adverse effects in complexity and maintenance cost especially due to the requirement of multiple spare parts [17].

A configuration with a number of engines with lower nominal power to operate in the low loads can improve the environmental and economic performance of the ship. For that reason, in this case study it is not assumed that all engines have the same nominal power. However, the number and nominal power of engines is selected to satisfy the power requirements. In specific, it is assumed that the total power installed needs to cover the power demand in the most demanding operational phase with one engine out of operation and the rest running at 90% load of their nominal power [17].

Accordingly, the components are selected to satisfy the peak requirements and also be operated efficiently. It is assumed and modelled that the power is distributed among the components in a way that they are operate between the regions of 70-90% of their nominal power as that is recognised as the most efficient. In addition, in every operational phase the minimum number of components

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[1] The storage and treatment of the fuel are considered.

[2] Technology with internal reformer.

required to cover the energy demand are used, in order to reduce maintenance costs and operation in low efficiency regions that leads in the increase of fuel cost and emissions.

4. Results

A set of dominant solutions is derived and indicative results for the most sustainable configurations are presented in this section. A sensitivity analysis of projected prices in 2030 of emerging technologies and fuels is performed, in order to illustrate the changes on the optimum configurations in the future.

4.1. Bi-objective optimisation results

In Fig. 2, the results from the bi-objective optimisation on the life cycle costs (LCC) and the CO_2 lifetime emissions are presented. All the points of the curve belong to the Pareto front and no other solution exists that can improve the performance in one objective without reducing the performance of at least one of the other objectives. Each point of the curve describes one optimum ship energy systems configuration according to the objectives. All the solutions presented comply with the IMO regulations for SOx, NOx emissions and the EEDI regulations for energy efficiency. From Fig. 2, it is evident that there is a number of optimum solutions for the investigated cruise ship configurations. The marked solution with X in Fig. 2. does not belong to the Pareto front and denotes the configuration used currently in most cruise ships of similar size.

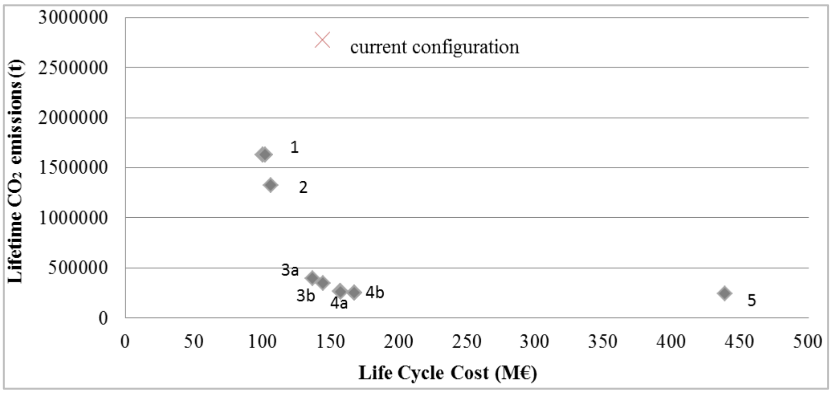

Fig. 2. Bi-objective optimisation results

In Table 2, the configuration for each solution is outlined, whereas the baseline configuration details is also included (first row). The solutions 3a and 3b as well as 4a and 4b have the same configuration, however the nominal power and the LCC and CO_2 lifetime emissions vary, as it is displayed in Table 2. In addition, it is evident that the performance of the traditional solution is not included in the optimum solutions set identified and has the worst performance regarding the CO_2 emissions. Solution 3b appears to have the same LCC as the configuration currently used; however the CO_2 emissions are dramatically less.

In the majority of the results of Fig. 2., the gas injected dual fuel engines are selected as optimum and in only few cases the diesel engines operating with HFO and switching to LSHFO in order to comply with the SOx regulations. The fuel cells technology, despite their higher cost, is included in the optimum solutions in combination with the pre-mixed dual fuel engines and it offers the best performance regarding the carbon footprint. The number of the engines are eight, in contrast with the baseline configuration with the six engines. A configuration with four engines with lower nominal power and four with higher shows an optimum performance and only in few cases the solutions have the same nominal power as it is the current practice. It is observed that the total nominal power installed is larger than the base case in some solutions; in those cases a further analysis shows that the higher energy content on the exhaust gas of the engines in combination with the larger WHR (dimensioning of the WHR is proportional to the main engines nominal power) improves the total efficiency of the power plant. The increased wasted energy covers a part of the thermal energy demand and as a result the emissions and the fuel consumed from the thermal boilers are reduced. In addition, instead of the traditional operational management with equal load sharing that might lead to a low load operation of the engines it is preferred from the optimisation two different sizes of engines larger and smaller engines that operate on a more efficient load. The emission reduction technologies either the EGR for the dual fuel gas injected or SCR for the diesel engines are selected in order to comply with the Tier III. The WHR is included in all of the solutions. For the thermal boiler in some cases the gas fired boiler is preferred and in other solutions the oil fired boiler running with LSHFO or HFO is selected.

Table 2. Configurations of Fig. 2.

	LCC (M€)	CO_2 (1000 tonnes)	Engine			Emission reduction technology	Energy efficiency technology	Thermal Boiler
			Type	Fuel	Nominal Power (kW)			
Baseline	145	2780	6/ diesel	HFO	12000	SCR+ fuel switch	Economiser	oil fired (HFO)
1	100	1580	4/ gas injected dual fuel	NG	16000	EGR	WHR	gas boiler (NG)
			4/ gas injected dual fuel	NG	2000	EGR		
2	105	1325	4/ gas injected dual fuel	NG	16000	EGR+CC	WHR	oil fired (HFO)
			4/ gas injected dual fuel	NG	2000	EGR +CC		
3(a)	135	400	4/ gas injected dual fuel	NG	8000	EGR +CC	WHR	gas boiler (NG)
			4/ gas injected dual fuel	NG	10000	EGR +CC		
3(b)	145	350	4/ gas injected dual fuel	NG	6000	EGR +CC	WHR	gas boiler (NG)
			4/ gas injected dual fuel	NG	12000	EGR +CC		
4(a)	150	290	4/ gas injected dual fuel	NG	10000	EGR+ CC	WHR	oil fired (LSHFO)
			4/ diesel	HFO	10000	LSHFO switch +SCR+CC		
4(b)	160	270	4/ gas injected dual fuel	NG	10000	EGR+ CC	WHR	oil fired (LSHFO)
			4/ diesel	HFO	10000	LSHFO switch +SCR+CC		
5	440	250	4/ pre-mixed dual fuel	NG	10000	CC	WHR	gas boiler (NG)
			4/ fuel cells	NG	10000	CC		

In the specific case study an 8% interest rate is adopted which is an average value for shipping investments. However, changes on the assumed value might affect the results. As it was expected an increase on this rate leads to a reduction on the operational costs of the alternative configurations and has a negative impact on the dual fuel solutions that are preferred against the diesel engines due to the lower operational costs. A 12% interest rate was investigated and a 4% increase on the adoption of diesel engines on the Pareto front, was observed. On the other hand, when a 5% interest rate was assumed, then the number of the fuel cells solutions on the Pareto front was increased by 13%.

4.2. Sensitivity analysis

The aim of this analysis is to understand how the cruise ship configurations respond in the forecasted costs of the fuels and technologies of the year 2030. The fuel prices scenarios are according to the global status quo, business as usual scenario in [35]. The established technologies prices are considered the same and only the emerging technologies prices are projected in the year of 2030. The fuel cells and carbon capture system projected cost follows the [36]. The scenario in Table 3 is used for the sensitivity analysis.

Table 3. Projected costs in 2030

Fuels	Cost Percentage Change
HFO	+6 %
NG	-5%
LSHFO	+4%
MGO	+6%
Emerging Technologies	**Cost Percentage Change**
Carbon Capture System	-25%
Fuel Cells	-60%

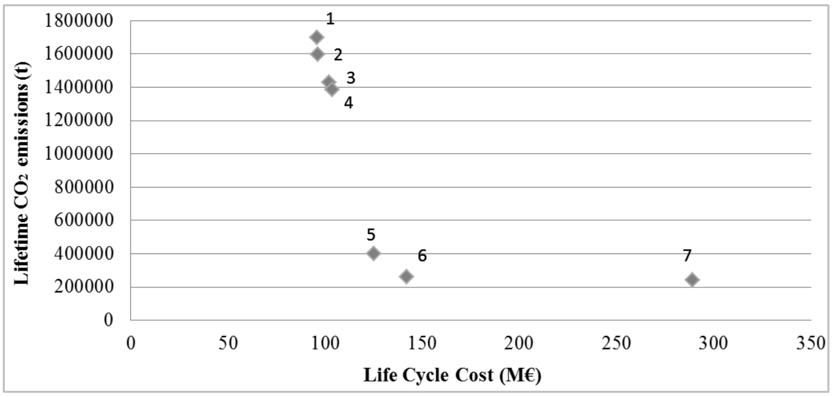

Fig. 3. Bi-objective optimisation results with 2030 scenarios

Table 4. Configurations of Fig. 3.

	LCC (M€)	CO_2 (1000 tonnes)	Engine			Emission reduction technology	Energy efficiency technology	Thermal Boiler
			Type	Fuel	Nominal Power (kW)			
1	95	1695	4/ gas injected dual fuel	NG	8000	EGR	none	gas boiler (NG)
			4/ gas injected dual fuel	NG	10000	EGR		
2	96	1600	4/ gas injected dual fuel	NG	16000	EGR	WHR	oil fired (HFO)
			4/ gas injected dual fuel	NG	2000	EGR		
3	102	1430	4/ gas injected dual fuel	NG	16000	EGR +CC	none	oil fired (LSHFO)
			4/ gas injected dual fuel	NG	2000	EGR +CC		
4	103	1385	4/ pre-mixed dual fuel	NG	16000	CC	WHR	oil fired (LSHFO)
			4/ pre-mixed dual fuel	NG	2000	CC		
5	125	400	4/ gas injected dual fuel	NG	10000	EGR +CC	WHR	gas boiler (NG)
			4/ gas injected dual fuel	NG	8000	EGR +CC		
6	140	260	4/ gas injected dual fuel	NG	10000	EGR+ CC	WHR	gas boiler (NG)
			4/ diesel	LSHFO	10000	SCR+CC		
7	290	250	4/ pre-mixed dual fuel	NG	10000	CC	WHR	gas boiler (NG)
			4/ fuel cells	NG	10000	CC		

In Fig. 3., the results from the bi-objective optimisation are displayed and in Table 4 the configurations of the Pareto front are presented. It can be derived from the results of the sensitivity analysis that the optimum ship energy systems follow the same pattern as the results on Fig. 2. However, a great difference among the results is that the life cycle cost is decreased drastically, due to the future projected prices, therefore making the environmental technologies and the natural gas more appealing. For this reason, the diesel engines are included in 30% of the solutions comparing to the 45% in the previous scenario. The fuel cells are included in 10% of the optimum solutions comparing to the 5% that was identified on the results of Fig. 2. Similarly the carbon capture is observed in 80% of the solutions whereas previously it was on the 70% of the optimum solutions.

In addition the gas boiler is on 70% of the solutions, comparing with the 30% that was in the base case.

5. Discussion

5.1. Suggested cruise ship energy systems

It is evident from the results in Fig. 2. that the current ship energy systems configuration has the worst performance regarding the carbon footprint comparing with the solutions from the optimisation, whereas the life cycle cost is quite low (145 million €). However, there are still other solutions that provide even lower life cycle cost, as it is evident from Table 2 and Fig. 2., and at the same time have a better environmental impact. Even though the capital cost of the dual fuel engines is higher comparing with the diesel engines due to the feeding and storage system for the fuel, overall the LCC is improved due to the lower lifetime fuel cost of dual fuel engines.

It is evident from the results that there are different configurations and combinations that can manage to improve the carbon footprint of the ship energy systems. Another important conclusion from the results is that the performance of the energy systems is improved when not all the engines have the same nominal power. When half of the engines have a smaller nominal power than the rest, the energy systems work efficiently both in low and high loads. In addition to the previous comment, in all the solutions of the optimisation eight engines are selected leading to four engines with low nominal power and four with greater in most cases, comparing with the base case configuration of six engines with the same power.

The technologies that are included in the optimum solutions are the dual fuel technologies and in few cases the diesel engine or the fuel cells. In the few cases when the diesel engine is among the optimum energy systems, fuel switch with low sulphur fuel is preferred in order to comply with the sulphur limits inside ECA areas. The scrubber technology is not selected in any of the solutions, due to the increase on both operational and capital cost. This contradicts the baseline configuration that includes diesel engines operating with HFO mostly, whilst the current practise to comply with the SOx regulations is with scrubbers or in some cases LSHFO switch. In all of the solutions, the WHR technology offers an improvement on the environmental and economic impact of the energy systems, proving to be a technology that can improve the efficiency of the cruise ship energy system. The carbon capture technology is an innovative technology that has not been yet implemented on cruise ships, and even though it has a high impact on the cost, it manages to decrease greatly the CO_2 emissions. For the thermal boiler, the gas fired boiler provides a solution with a more environmentally friendly performance comparing with the oil fired boiler, thus it is a possible alternative that can improve the environmental footprint of the cruise ships.

According to the results from the future scenarios, the optimal technologies are following similar pattern with the base case scenario; only the cost is drastically lower. Another difference is that the dual fuel engines are dominant among the solutions and the diesel engines less frequently included in the results. In addition, the gas fired boiler has a higher percentage on the optimum solutions. This comes as a result from the future fuels prices, since the natural gas is the only fuel that is expected to drop in price. It is evident that when the cost of carbon capture and the fuel cells is decreased around 25% and 60% respectively in the future scenarios, these technologies are included much more in the optimum solutions.

5.2. Limitations and future work

The genetic algorithm might not be able to provide the whole Pareto front, even though the NSGA-II exhibits a high capability in identifying the Pareto front. Only the main energy producers are included in the study and the modelling is high level, however the results do not aim to serve as an in depth representation of reality. In addition, only the steady-state conditions are investigated because the transient operation of the systems is out of the scope of this study.

As future research directions, a multi-criteria analysis method could be beneficial in order to derive a single optimum solution from the set of non-dominated solutions of the Pareto front. A further sensitivity analysis with future policy scenarios could be performed in order to facilitate a better understanding of the future optimal cruise ship energy systems configuration.

6. Conclusions

The results of this study showed the need for a detailed analysis of the alternative energy systems configurations of a cruise ship. The quantification and evaluation of both environmental and economic performance of the energy systems allows to manage the trade-offs among the objectives and leads to an informed decision for the selection of a configuration that improves the ship energy systems sustainability. The implementation of an optimisation method reduces drastically the computational time of evaluating all the possible combinations and gives the opportunity to include more technologies and perform sensitivity analysis on the parameters. The inclusion of the operational profile as well as the aging factors of the technologies leads to the evaluation of the actual lifetime performance of the ship energy systems, according to the cruise ship operations.

The Pareto front of the non-dominated solutions, offers a range of optimum solutions and not just a single one, thus allowing better understanding of the range of alternatives, especially for a long-term investment with a future with many uncertainties. The results of the sensitivity analysis offer an insight of the optimum configurations in the year 2030 according to the maturity of the emerging technologies and the forecast of the fuel prices; thus handling some of the future uncertainties.

The main findings of this work are summarised as follows:

- The current cruise ship energy systems configuration is not included in the Pareto front of optimum solutions; there are better performing solutions identified in each of the criteria examined.
- The dual fuel engine generators operating with natural gas offer the best performance and in the future it seems that it could be the dominant technology due to a combined best performance in both economic and environmental criteria.
- WHR technology improves the energy efficiency of the ship energy systems.
- Fuel cells in both current and future scenarios have a very high economic impact however improve the carbon footprint of the ship energy systems so they are among the optimum solutions.
- Two set of engines with different nominal power in order to cover efficiently both the low and high loads are improving the performance of the systems.

The results of the case study constitute a basis for future analysis for the environmental and economic improvement of the cruise ship energy systems.

Acknowledgments

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Nomenclature

capex	Capital expenditure (€)
E	Emissions (g)
ir	Interest rate (%)
opex	Operational expenditure (€)
Y	lifetime operations (year)

Subscripts and superscripts

CO_2 Carbon dioxide
NOx Nitrogen oxides
SOx Sulphur oxides

References

[1] IMO. Annex 19-Resolution MEPC.203(62), Amendments to the annex of the protocol of 1997 to amend the international convention for the prevention of pollution from ships, 1973, as modified by the protocol of 1978 relating thereto. 2011.

[2] IMO. Annex 5, Resolution MEPC.245(66), Guidelines on the Method of Calculation of the Attained Energy Efficiency Design Index (EEDI) for New Ships. 2014.

[3] IMO. Annex 9, Resolution MEPC.213(63), 2012 Guidelines for the Development of a Ship Energy Efficiency Management Plan (SEEMP). 2012.

[4] EU. Proposal for a Regulation of the European Parliament and of the Council on the Monitoring, Reporting and Verification of Carbon Dioxide Emissions From Maritime Transport and Amending Regulation (EU) No. 525/2013 – Political Agreement. 2014.

[5] Wang X, Teo C-C. Integrated hedging and network planning for container shipping's bunker fuel management. Marit Econ Logist 2013;15. doi:10.1057/mel.2013.5.

[6] Burel F, Taccani R, Zuliani N. Improving sustainability of maritime transport through utilization of Liquefied Natural Gas (LNG) for propulsion. Energy 2013;57:412–20. doi:10.1016/j.energy.2013.05.002.

[7] Biert L van, Godjevac M, Visser K, Aravind P V. A review of fuel cell systems for maritime applications. J Power Sources 2016;327:345–64. doi:10.1016/j.jpowsour.2016.07.007.

[8] Yang ZL, Zhang D, Caglayan O, Jenkinson ID, Bonsall S, Wang J, et al. Selection of techniques for reducing shipping NOx and SOx emissions. Transp Res Part D Transp Environ 2012;17:478–86. doi:10.1016/j.trd.2012.05.010.

[9] Wang C, Corbett JJ, Winebrake JJ. Cost-effectiveness of reducing sulfur emissions from ships. Environ Sci Technol 2007;41:8233–9. doi:10.1021/es070812w.

[10] Zhou P, Wang H. Carbon capture and storage - Solidification and storage of carbon dioxide captured on ships. Ocean Eng 2014;91:172–80. doi:10.1016/j.oceaneng.2014.09.006.

[11] Ovrum E, Bergh TF. Modelling lithium-ion battery hybrid ship crane operation. Appl Energy 2015;152:162–72. doi:10.1016/j.apenergy.2015.01.066.

[12] Armellini A, Daniotti S, Pinamonti P, Reini M. Analysis of alternative energy production systems for a large cruise ship to meet new IMO regulations. Part A: GTs as prime movers. Appl Energy 2018;211:306–17. doi:10.1016/j.apenergy.2017.11.057.

[13] Dimopoulos GG, Kougioufas A V., Frangopoulos CA. Synthesis, design and operation optimization of a marine energy system. Energy 2008;33:180–8. doi:10.1016/j.energy.2007.09.004.

[14] Wik C. Tier III technology development and its influence on ship installation and operation. CIMAC Congr. 2013, 2013.

[15] Thiem C, Gentner C, Ackermann G. Methanol Powered Fuel Cell Systems for Marine Applications. Int Conf Shipp Chang Clim Technol Oper Logist POLICIES Towar Meet 2050 Emiss TARGETS 2015.

[16] Baldi F, Ahlgren F, Melino F, Gabrielii C, Andersson K. Optimal load allocation of complex ship power plants. Energy Convers Manag 2016;124:344–56. doi:10.1016/j.enconman.2016.07.009.

[17] Baldi F, Marechal F, Tammi K. Process integration as a tool for the improvement of cruise ships energy efficiency. Conf. Shipp. Chang. Clim., London, UK: 2017.

[18] Shu G, Liu P, Tian H, Wang X, Jing D. Operational profile based thermal-economic analysis on an Organic Rankine cycle using for harvesting marine engine's exhaust waste heat. Energy Convers Manag 2017;146:107–23. doi:10.1016/j.enconman.2017.04.099.

[19] Mondejar ME, Ahlgren F, Thern M, Genrup M. Quasi-steady state simulation of an organic Rankine cycle for waste heat recovery in a passenger vessel. Appl Energy 2017;185:1324–35. doi:10.1016/j.apenergy.2016.03.024.

[20] Trivyza NL, Rentizelas A, Theotokatos G. A novel multi-objective decision support method for ship energy systems synthesis to enhance sustainability. Energy Convers Manag 2018. doi:10.1016/j.enconman.2018.04.020.

[21] MAN Diesel &Turbo. MAN L35/44DF Project Guide – Marine Four-stroke dual fuel engines compliant with IMO Tier II. 2017.

[22] MAN Diesel & Turbo. MAN L32/44 GenSet Project Guide – Marine Four-stroke diesel engine compliant with IMO Tier II. 2016.

[23] Wärtsilä. Wärtsilä Project Guides. 2017.

[24] MAN Diesel &Turbo. Project Guide: MAN L35 / 44DF Four-stroke dual fuel engines compliant with IMO Tier II 2017.

[25] Cichowicz J, Theotokatos G, Vassalos D. Dynamic energy modelling for ship life-cycle performance assessment. Ocean Eng 2015;110:1–13. doi:10.1016/j.oceaneng.2015.05.041.

[26] SNAME. Marine Diesel Power Plant Practises, T&R Bulletin 3-49. 1990.

[27] Alkaner S, Zhou P. A comparative study on life cycle analysis of molten carbon fuel cells and diesel engines for marine application. J Power Sources 2006;158:188–99. doi:10.1016/j.jpowsour.2005.07.076.

[28] Wärtsilä. Wärtsilä Environmental Product Guide. Finland: 2015.

[29] Wik C. Low emission engine technologies for future Tier 3 legislations- Options and case studies. J Shipp Trade 2016:1–34. doi:10.1186/s41072-016-0009-z.

[30] IMO. Annex VI-Regulations for the prevention of Air Pollution from Ships. Sulphur Oxides (SOx)-Regulation 14 2005.

[31] Trautmann H, Wagner T, Naujoks B, Preuss M, Mehnen J. Statistical Methods for Convergence Detection of Multi-Objective Evolutionary Algorithms. Evol Comput 2009;17:493–509. doi:10.1162/evco.2009.17.4.17403.

[32] Chaudhari P, Dharaskar R, Thakare VM. Computing the Most Significant Solution from Pareto Front obtained in Multi-objective Evolutionary. Ijacsa 2010;1:63–8.

[33] Deb K. Multi-Objective Optimization Using Evolutionary Algorithms : An Introduction 2011:1–24.

[34] Baldi F, Ahlgren F, Nguyen T-V, Gabrielii C, Andersson K. Energy and exergy analysis of a cruise ship. Effic. Cost Optim. Simul. Environ. Impact Energy Syst., France: 2015.

[35] Lloyd's Register, UCL. Global Marine Fuel Trends 2030. 2014.

[36] Wittenstein M, Rothwell G. Projected Costs of Generating Electricity. 2015.