Impact of carbon pricing on the cruise ship energy systems optimal configuration

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Abstract

The shipping industry has been facing increasing challenges due to the stringent regulations for anthropogenic emissions limits, the new targets for carbon emissions reduction and the potential carbon pricing introduction. These have led to an upsurge of activities towards improving the environmental footprint of cruise ships. This study investigates the impact of carbon pricing on the cruise ships optimal power plant configuration. Mathematical models are used to estimate the performance of the cruise ship energy systems. A novel bi-objective optimisation method for the cruise ship energy systems synthesis is developed, which employs the Non-Sorting Genetic Algorithm II optimisation algorithm and uses as objectives the Life Cycle Cost and the lifetime carbon emissions. Cruise ship configurations that perform optimally under carbon pricing scenarios while complying with the air emissions regulations are identified. The results show that the baseline configuration does not belong to the optimal solutions. Solutions including carbon capture, waste heat recovery and dual fuel generator sets that operate with natural gas or methanol can reduce drastically the carbon emissions. The optimisation identified solutions that reduce the Life Cycle Cost by 40% compared to the baseline configuration despite increasing their capital cost, whilst reducing of the carbon emissions more than 37%.

Keywords

Cruise ships, carbon pricing policy, energy systems, optimisation, carbon emissions, life cycle cost

1. Introduction

Shipping operations play a significant role in the global economy and international shipping is estimated to carry around 90% of the global trade in volume and more than 70% in value [1]. It is forecasted that by the year 2030 the annual seaborne trade volume will be two times greater than the baseline, reaching around 20 billion tonnes [2]. This increasing market growth leads consequently to significant environmental impact. The International Maritime Organisation (IMO) has introduced stricter emission control areas for NOx and SOx emissions and it is expected in the future that more areas are going to be included, like the Mediterranean sea [3]. In addition, stringent sulphur limits are going to be implemented for the global waters from 2020 [4].

Regulations to improve the ship energy efficiency and reduce the GHG emissions have also been introduced and further pressure to the ship owners/operators is foreseen in the future. However, despite this regulatory framework, the shipping operations still have a great impact on the worldwide CO_2 emissions and it is forecasted that even though shipping now accounts for only 2.2% of the global CO_2 emissions, it might reach 17% by 2050 if no measures are taken [5]. A reduction of carbon emissions around 90% is required from 2010 to 2050 [6] in order for the shipping operations to contribute beneficially to the global target of keeping the temperature increase below 2^{o}C. Recently the IMO, acknowledging the significant contribution of the shipping operations on the global carbon emissions, set a target on CO_2 emissions from ships [7]. Along these lines, it has been discussed to introduce shipping operations into the European Emission Trading Market Scheme (EU ETS) for CO_2 emissions [8] as well as to tax the carbon emissions, similarly to the land-based power plants.

As a result, alternative configurations compared to the traditional ones need to be explored in order to comply with the emissions regulations and improve the environmental impact of ship energy systems. For example, with the new limits for sulphur content on marine fuels, the traditional configurations with diesel engine operating with Heavy Fuel Oil (HFO) cannot be employed stand alone. The most predominant way to reduce SOx and NOx emissions from diesel engines is by using emission after treatment technologies [9]. Another alternative is to introduce other low sulphur content fuels including natural gas and methanol. The usage of these fuels can also result in reducing the NOx emissions [10]. The CO_2 emissions can be also reduced by including carbon capture and storage systems, or using biofuels and hydrogen [11].

In this respect, the ship energy systems selection has become a very challenging and complex procedure, especially since retrofitting the energy systems might be challenging in some cases according to [12]. Finally, retrofit a new built might cost more than 40% more than a new built [13].

1.1. Literature review on cruise ship energy systems

Improving the cruise and passenger ships energy systems efficiency has recently gained great attention from both industry and academia. The energy and exergy analysis of a cruise ship energy system configuration in order to improve its energy efficiency was investigated in [14]. In addition, there has been great interest in the exploitation of the wasted energy from the engine exhaust gas in order to improve the cruise ships energy efficiency. The techno-economic optimisation of a propulsion system with WHR has been addressed in [15]. The simulation of an organic Rankine cycle (ORC) performance analysis was presented in [16]. The techno-economic analysis of and ORC was reported in [17]. The working fluid optimisation of an ORC on a diesel propulsion plant was discussed in [18].

Previous studies have also investigated the techno-economic performance of specific propulsion systems of cruise ships. The fuel consumption and installation weight optimisation of three different propulsion system configurations was investigated in [19]. In addition, the economic investigation of three alternative propulsion systems was performed in [20]. A combined gas turbine electric and steam configuration was optimised considering economic objectives in [21].

Complex hybrid systems have also been discussed as an alternative to improve the ship energy systems energy efficiency as well as the ship environmental footprint. The load allocation with economic considerations of a hybrid system has been discussed in [22]. The energy efficiency of a hybrid system was optimised in [7]. The simulation of the performance of a hybrid system that includes fuel cells and batteries was presented in [23]. The investigation of a hybrid system including photovoltaic system was reported in [24]. Finally, the technical analysis of the fuel cells for high complexity energy systems like those on cruise ships, in order to improve the energy systems environmental performance was addressed in [25].

In the literature, the focus has been mostly on the analysis of specific technologies or propulsion systems of the cruise ships with techno-economic objectives. However, the cruise ship energy systems are complex and have a large number of interconnections. In addition, due to the recent and upcoming strict air emissions regulatory requirements, the exploration of exhaust gas after-treatment or alternative technologies to comply with these regulations is necessary. As a result, an integrated approach of assessing all the components of the ship energy system is required in order to improve the energy efficiency and environmental impact of cruise ship energy systems.

Furthermore, due to the variety of technologies and combinations in order to assess the possible alternative cruise ship energy systems, an optimisation method is required to evaluate all the potential solutions and identify the optimal. However, previous studies have focused on the investigation of a small number of specific alternative configurations without exploring alternative options for the integrated energy systems.

Finally, due to the expected future CO_2 target regulations and the possibility of introducing carbon policies, there is an interest towards the investigation of ship energy systems configurations that can mitigate the CO_2 emissions whilst keeping the lifecycle cost impact to a minimum level. Even though in the literature authors have investigated technologies in order to improve the energy efficiency and reduce the CO_2 emissions, only few studies considered the impact of carbon pricing policies; this was done by including a fixed price for the CO_2 emissions taxation [26].

1.2. Aim

The aim of this study is to identify the cruise ship energy systems with the optimal performance under future carbon pricing scenarios by considering the minimisation of both the life cycle cost and the lifetime CO_2 emissions objectives, whilst complying with the NOx and SOx emissions regulations. It is the first work to investigate the optimal integrated cruise ship energy systems configuration not only for the current carbon emissions regulatory status but also for potential carbon pricing policy scenarios. This investigation is critical for cruise ships, due to the continuous growth of the sector, its significant contribution to the global emissions, the high energy demand and complexity of the cruise ship energy systems and the significant cost implications of the potential carbon pricing policies. In this respect, various carbon pricing policy scenario impact on the optimal cruise ship energy systems configurations is investigated, in order to provide support to the cruise ship owners and policy makers regarding the potential optimal configurations in light of the prospective carbon pricing regulations.

The rest of the paper is organised as follows. The cruise ship characteristics are discussed in Section 2. The model and optimisation method employed to estimate the cruise ship energy systems optimal configurations is presented in Section 3. The investigated carbon pricing policy scenarios are shown in Section 4. The investigated case study is presented in Section 5. The results are discussed in Section 6, whereas the concluding remarks are presented in Section 7.

2. Cruise ships

The cruise ship industry is a growing sector and in the recent years it is one of the fastest rising segments of the tourism sector [27]. Due to this continuous growth, it has been reported that around $25bn worth of cruise ships have been ordered from 2016 to 2022 [28]. In 2014, the revenues from cruise ship operations globally accounted for $37bn [29].

At the same time, it is estimated that the annual global cruise ships fuel consumption can be more than 30 million tonnes of fuel oil constituting a 10% of the overall annual consumption of ships [30]. The environmental impact of cruise ships is also very high, with estimations showing that cruise ships have more CO_2 emissions per passenger-kilometre from economy class aviation [31]. Cruise ships emitted 35 million tons of CO_2 emissions corresponding to 4.4% of the emitted CO_2 from the global ship fleet for the year 2012 [32].

2.1. Cruise ship energy systems

Cruise ships constitute one of the highly energy intensive ship types with complex energy systems, due to their high energy demand for the passengers' accommodation and services [21]. A common configuration for the cruise ship power plant is of the 'fully electric' type [33]. The typical configuration for a fully electric cruise ship, with size 140,000 GT similar to the one investigated herein, is depicted in Figure 1. Cruise ships of that size account for a considerable part of the overall tonnage of the cruise ship fleet and are identified as representatives high-efficiency conventional cruise ships [34].

In a fully electric configuration, the electric power is distributed to the electric system switchboards to fulfil the electric power requirements and provide power for the electric motors to drive the ship propellers as presented in Figure 1. Thermal boilers along with the economiser provide the saturated steam for the ship heating services. In addition, emission reduction technologies are installed in order for the ship to comply with the emission regulations.

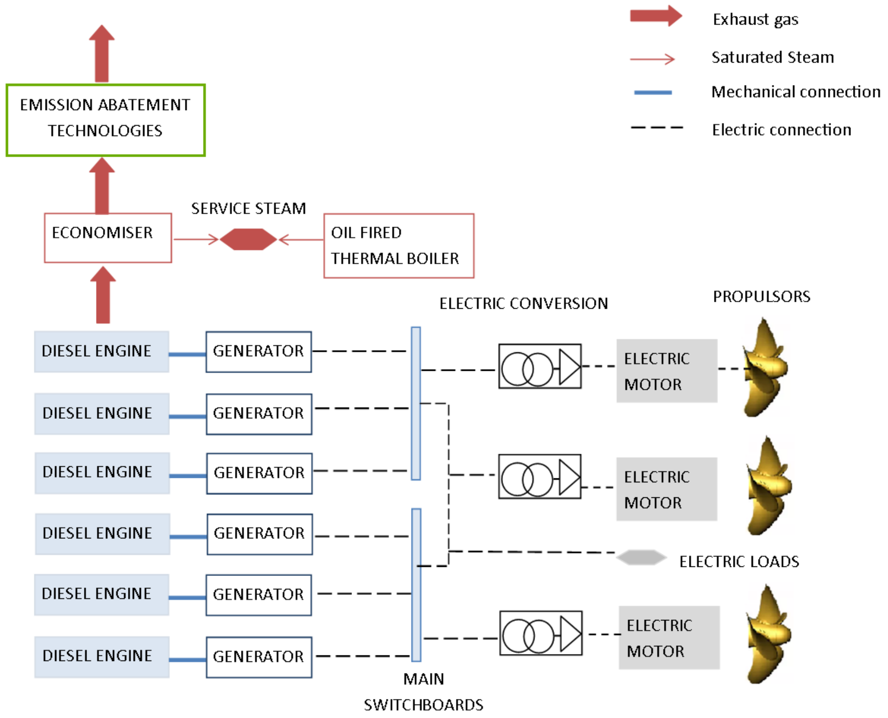

Figure 1: Typical configuration for a 140,000 GT cruise ship

Along with the power demand for the propulsion, electric power and auxiliary systems, the passenger ships, compared to the other ship types, require a great amount of power for operating the heating, ventilation and air conditioning systems, as well as for generating the required amount of fresh water. In Figure 2, the energy distribution of a cruise ship is presented, derived from on-board measurements collected within five years of operation of the investigated ship. Similar results are found in the literature for large cruise ships [35]. As it is evident from Figure 2, a significant percentage of the total energy is dedicated to the passengers' needs.

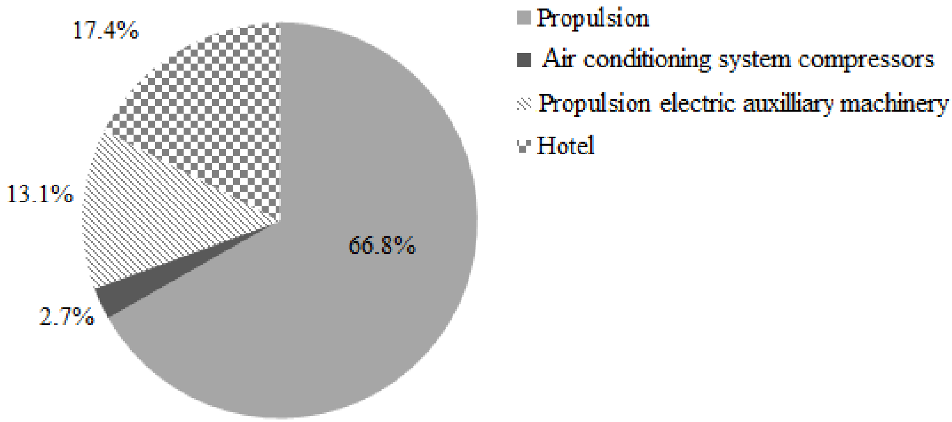

Figure 2: Cruise ship energy distribution from on-board measurements

Cruise ships sail on coastal routes and spend more than 30% of their operating time in ports [14]. This results in a significant amount of emissions in the coastal areas leading to serious health problems for the population in the surrounding area [36]. The most popular area for the cruise ships operation is the Caribbean, considered as a dominant market for the cruise industry, and lately the Mediterranean, where operations considerably increase especially during the summer seasons [37]. Together those regions account for 70% of the global cruise industry in bed-day terms. In addition, during the summer seasons, Alaska and Northeast Atlantic as well as Australia share the rest of the cruise ship market [37]. The Asian market is also gaining a share of the cruise market in the year 2017 it was around 10% of the global market [38]. It is evident that the cruise ships greatest market is on seas that belong to the ECA or areas that are possible to be characterised as ECAs in the future.

3. Modelling and optimisation of cruise ship energy systems

The authors have presented in [39] a generic multi-objective decision support method for optimising the design of the ship energy systems configurations considering economic and environmental objectives, which was applied on a tanker ship. In this work, this method is adapted and applied for the case of a cruise ship. The proposed method flowchart is displayed in Figure 3.

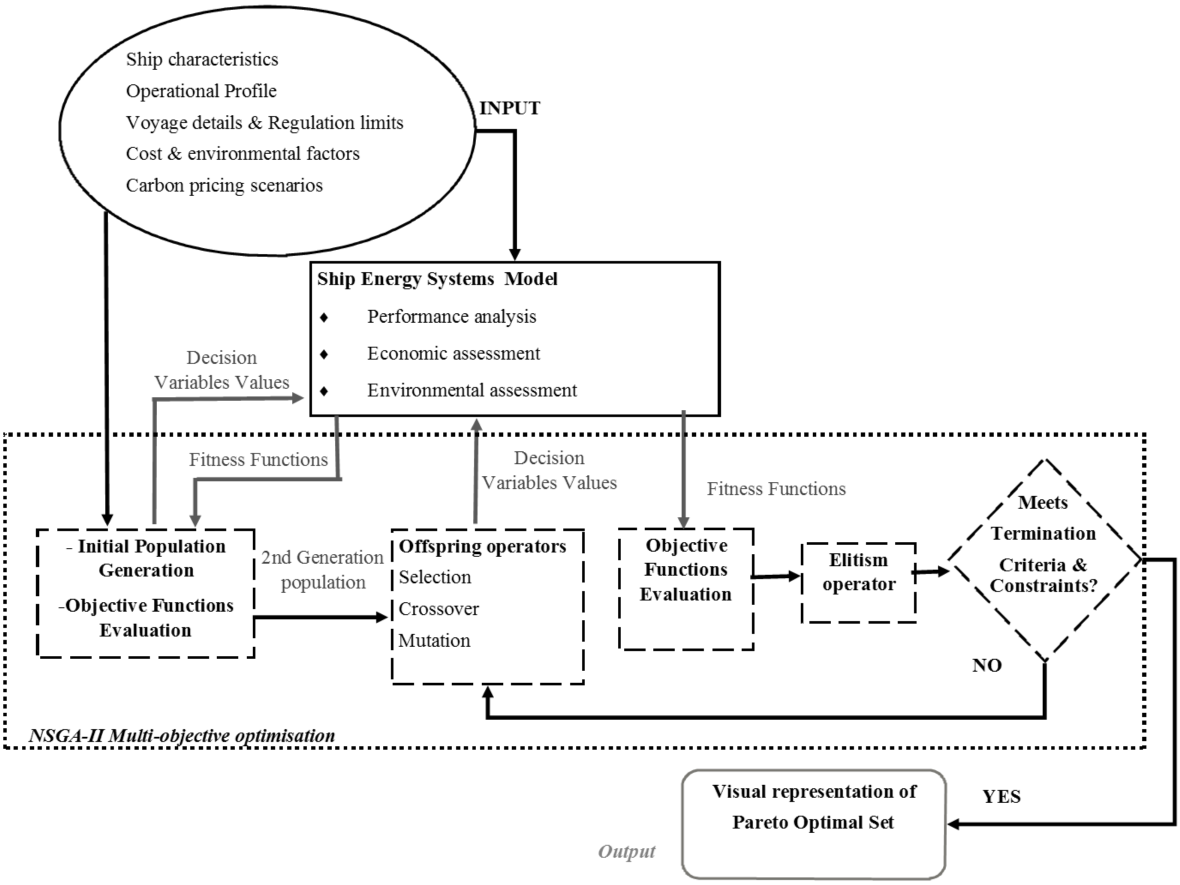

Figure 3: Flowchart for the optimal cruise energy systems selection

A number of input parameters are employed by the ship energy systems model in order to simulate the investigated cruise ship energy systems environmental and economic performance. An initial population is randomly generated and the decision variables values are provided as input to the ship energy systems model. Following a population generation, each individual of the population is allocated into a rank according to the number of individuals it dominates and is dominated. The fitter solutions are allocated to the highest rank based on the two objectives values. The best N (with N being the population) individuals of the generation enter a mating pool. The generation of new individuals by using the offspring operators, the selection of parents as well as the crossover and mutation are performed according to the genetic algorithm principles. During the reproduction process, the mating pool will include more solutions that belong in the highest rank. In the selection process, the crowding distance measure is employed in order to obtain a uniform and diverse Pareto front; thus, the solutions that are not crowded will be given a higher preference. The produced offsprings and the current population are combined and ranked according to the process described above. After the ranking process, the best N solutions are included in the new population. According to the elitism operator, a percentage of the solutions that belong to the highest rank passes unchanged to the next generation. This process is repeated, as it is demonstrated in Figure 3 until the termination criteria are met and the final Pareto front of optimum solutions is visualised. The proposed method was validated in the authors previous work that can be found in [39], where it was concluded that the solutions are adequately robust and the model manages to capture the input parameters variation.

3.1. Cruise ship energy systems modelling

For the specific case study, the previously published ship energy systems model [39] was extended and adapted to suit the requirements and characteristics of the cruise ships. Several alternative types of electric power producers, in specific, diesel engines, dual fuel engines, fuel cells and turbo-generator system are investigated. Combined gas turbine cycle is a promising technology for cruise ships, however gas turbines in part-loads exhibits lower efficiency [40]. This leads to high primary energy consumption [41]. Therefore, the gas turbines and combined cycle configurations are not considered in this work. Furthermore, fuel cells are considered as solutions for producing part of the ship electric energy since they exhibit great potential as components of complex energy systems [25].
Regarding fuel cell technologies, Molten Carbon Fuel Cells (MCFCs) are technology modelled in this work. MCFCs are one of the dominant technologies used in large scale stationary power plants [42], after decades of development [43]. In addition, MCFCs are a mature technology and have been successfully used on board ships [44]. MCFCs (as well as Solid Oxide Fuel Cells SOFCs) in most applications are integrated with a fuel reformer and thus provide fuel flexibility instead of other fuel cells type that can only use hydrogen [45]. In addition, MCFC and SOFC are high temperature fuel cells compared to the Proton-exchange membrane fuel cells PEMFC. Thus, a greater system efficiency can be obtained by combining them with a waste heat recovery technology [46]. Even though SOFCs are a very promising solution, they face challenges due to the very high temperature and the electrolyte material [47]. SOFCs are an emerging technology but their potential for scale up in marine applications is linked with further technological developments [48]. Currently, the fuel cells types that are more prominent for marine applications are the MCFC and PEMFC [49]. However, as PEMFCs operate by using pure hydrogen, it is likely that their usage will be limited to hydrogen fuelled ships [49]. Finally, additional fuels like methanol were considered for the main engines and fuel cells operation.

For all the considered cruise ship energy system components, mathematical models based on algebraic equations were employed to represent their performance parameters. The required input parameters, the employed equations as well as the derived output parameters are displayed in Table 1.

Table 1. Mathematical models of systems

<table>
<tr><th>Energy System</th><th>Input parameters</th><th>Modelled performance parameters</th><th>Output parameters</th></tr>
<tr><td>Main engine</td><td rowspan="4">• Operational Profile (power demand, frequency of occurrence)
• Performance of technologies
• Emission factors
• Cost factors
• Voyage details</td><td>• Specific fuel consumption
• Exhaust gas temperature
• Exhaust gas amount</td><td rowspan="3">• Capital Cost:
$capex = \sum_s C_{c,s} N_s P_{n,s}$
• Operational Costs
$opex = \sum_s fc_s C_f + \sum_s C_{m,s} P_{i,s}\, h + \sum_s \frac{E_{CO_2}}{10^6} t_{CO2}$</td></tr>
<tr><td>Thermal boiler</td><td>• Fuel consumption</td></tr>
<tr><td>WHR</td><td>• Superheated steam flow rate
• Generated electric energy from T/G</td></tr>
<tr><td>Emission reduction technology</td><td>• Chemical consumables cost
• Energy consumption</td><td>• CO_2, NOx, SOx Lifetime Emissions
$E_p = \sum_s EF(\frac{g}{g\ fuel}) fc_s$
or
$E_p = \sum_s EF(\frac{g}{kWh}) P_{i,s} h$</td></tr>
</table>

Regression analysis of the data gathered from engine manufacturers' project guides were used in this study to calculate the employed algebraic equations parameters. In specific, information for the marine four-stroke diesel engines performance parameters were derived from [50]. Information for the marine four-stroke dual fuel engines (operating with natural gas or methanol as the main fuel) were taken from [51]. The fuel cells energy consumption is modelled according to the data provided in [46]. The analysed energy system components performance parameters are considered functions of the respective load (L). The engines brake specific fuel consumption, exhaust gas mass flow rate, exhaust gas temperature and brake specific energy consumption equations and the derived values of the parameters of equations are provided in Appendix B.

3.2. Modelling assumptions and limitations

It is assumed that only two different types of generator sets can simultaneously be used in a configuration, since multiple engine types have adverse effects on the energy system complexity and maintenance cost, especially due to the multiple spare parts requirements, and it is avoided in practice [33]. The generator sets may have different nominal power, whereas the generator sets number and nominal power are selected to satisfy the ship power requirements. In the case where a WHR is installed, the contribution of the turbo-generator power is considered for the selection of the engines nominal power and size. The system components are selected to satisfy the peak power requirements, whilst operation closer to their most efficient points is pursued.

In the investigated cruise ship energy system, the load allocation (sharing) between the system components in each discrete operating point of the considered operating profile takes place according to the following procedure:

- The energy systems components are considered to operate with the following sequence: first, the FCs will be used till they operate between 70% and 90% of their nominal power in order to maintain their high overall efficiency [52]; in subsequence, the DF generator sets will be used till to operate at 90% of their nominal power and finally, the diesel sets will be used till to operate at 90% of their nominal power.
- For solutions that include components of different size, it is assumed that first the components of the smaller power will be operated (each one operating up to 90% of their nominal power) and then the components of the larger size (also each one operating up to 90% of their nominal power) till the total power demand is covered.
- For the cases where more than one engines of the same type need to operate for covering the ship power demand, even load sharing approach is assumed.
- It is assumed that the generator sets do not operate lower than 10% of the engines MCR, as operating in so low loads may cause various operational issues.

The carbon capture technology for the investigated cruise ship is modelled according to [53]; however, the detailed analysis of the technology impact on the ship design is not performed. In addition, it is assumed that the carbon capture technology cannot be used for completely capturing all the produced CO_2 emissions, and a constraint of less than 4% occupation of the ship payload from the carbon by-products is considered for practical purposes.

3.3. Bi-objective optimisation problem formulation

A bi-objective optimisation is solved considering as objectives the Life Cycle Cost, which is calculated by using Equation (1), and the lifetime CO_2 emissions which calculated by using Equation (2).

$$f_1 = capex + \sum_{k=1}^{Y} \frac{opex_k}{(1+dr)^k} \, , \tag{1}$$

$$f_2 = \sum_{k=1}^{Y} (E_{CO_2,me} + E_{CO_2,tb} - E_{CO_2,CC}) \, , \tag{2}$$

These two objectives were selected as the main focus is on identifying future cruise ship energy systems that can achieve CO_2 emissions reduction, which is the current challenge of the shipping industry. However, a number of constraints are imposed including the ones related to the required power demand, technical constraints regarding the incompatibility of certain technologies within a single configuration and finally regulatory constrains for the gas emissions in order to ensure that the ship satisfies the SOx and NOx emissions limits. The solutions are identified according to the non-dominating sorting described in Section 3. The terms in the right-hand side of Equations (1) and (2) are estimated according to Table 1. The detailed description of the constraints and assumptions of the problem can be found in Appendix A.

The optimisation decision variables for the generator sets and the thermal boiler selection are depicted in Table 2. The decision variables of the binary type (0,1) are used to indicate whether a component is included in the system. In addition, a set of integer variables are used with their values representing an alternative technology that could be a part of the ship energy systems.

Table 2. Optimisation decision variables

Decision Variables	Variable Type
generator set type	integer
number of generator sets	integer
generator set fuel type	integer
nominal power of generator set engine	integer [1]
thermal boiler type	integer
thermal boiler fuel type	integer
emission reduction technology existence	binary
waste heat recovery technology existence	binary

[1] the nominal power of the main engine is modelled as a discrete decision variable with a step of 1000 kW

The capital expenditure in Equation (1) for the generator sets and thermal boiler is estimated as a function of the respective component nominal power. The capital cost for the WHR and emission reduction technologies is expressed as a function of the installed nominal power. The operational expenditure entails the fuel and the maintenance costs.

The objective function of Equation (2) describes the lifetime CO_2 emissions from the investigated generator sets and the thermal boiler. The first two factors of Equation (2) denote the emissions from the ship engines and the thermal boiler, respectively, whereas the last factor is the emissions reduction due to the emission reduction technologies.

3.4. Optimisation algorithm

The presented problem is of the multi-objective combinatorial type and it is solved by employing the multi-objective evolutionary algorithm, NSGA-II, which is one of the most commonly used algorithms for similar problems [54]. This optimisation algorithm has been effectively used for the optimisation of energy systems with sustainability considerations in [55]. In addition it has been employed for ship energy systems with sustainability considerations in [56].

The fine-tuning of the NSGA-II algorithm is performed according to the Taguchi design of experiments for the following parameters: the population size, the percentage of solutions that is considered elite, the crossover fraction and the mutation related parameters. The employed optimisation algorithm parameters values and termination criteria are displayed in Table 3. The presented bi-objective optimisation synthesis problem was programmed and solved in the Matlab software.

Table 3: NSGA-II optimisation algorithm parameters

Parameter	**Value**
Crossover	0.8
Pareto Fraction	0.2
Populations size	2500
Scale	1
Shrink	1
Termination criteria	**Value**
Function tolerance	0.001
Generations	200
Stall Generations	100

4. Investigated policy scenarios

In this study, four scenarios are considered derived from the World Energy Outlook study [57] for assessing their potential impact on the optimal ship energy systems configuration. The adopted scenarios include the non-taxation scenario (NT) and the three carbon pricing policy scenarios (CP, NP, SD) as displayed in Figure 4. The three scenarios CP, NP and SD were derived by using interpolation considering the values forecasted for the European Union region in years 2025 and 2040 for the electric power, industry and aviation sectors assuming that the marine industry will follow. For the year 2018, the carbon policy price is set zero since in the shipping industry no carbon policy has yet been implemented. The considered scenarios details are as follows.

1. No tax (NT) scenario: assuming that carbon pricing will not be implemented and therefore, there is no cost for CO_2 emissions, which is the current situation in the marine industry.

2. Current policies (CP) scenario: considering only the momentum of the policies that have been implemented in the energy sector by the mid of year 2017.

3. New policies (NP) scenario: includes the existing policies as well as incorporates the ambitions of the policy makers in the energy sector.

4. Sustainable development (SD) scenario: entails policy scenarios required in order to comply with the 2030 agenda of United Nations for Sustainable Development, representing the vision of where the energy sector should go.

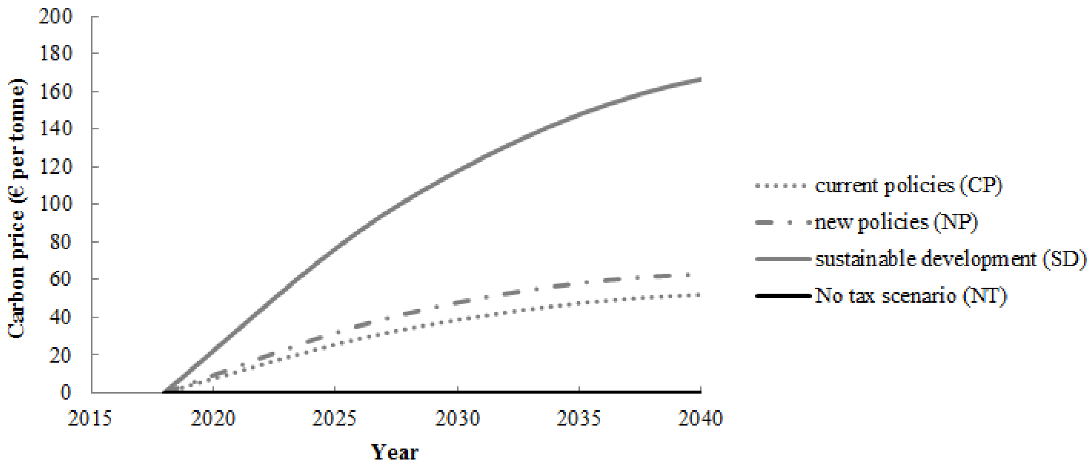

Figure 4: Carbon pricing policy scenarios adapted from [57]

5. Case study

The developed model was implemented for the case study of a cruise ship with a gross tonnage of 140,000 GT that can accommodate around 4000 passengers. It was assumed that the ship sails inside ECA waters, which is the most common scenario according to the cruise ships typical routes as it was discussed in the preceding sections. The ship lifetime performance is assessed for 25 years of operation, whereas it is assumed that the vessel is not operational 7% of her lifetime due to maintenance. For the calculation of the Life Cycle Cost, a 10% discount rate is used.

In this case study, the operational profile shown in Figure 5 was used in order to estimate the ship energy systems lifetime performance, it was derived from actual operational data measurements collected on-board a cruise ship for 5 years of operation.

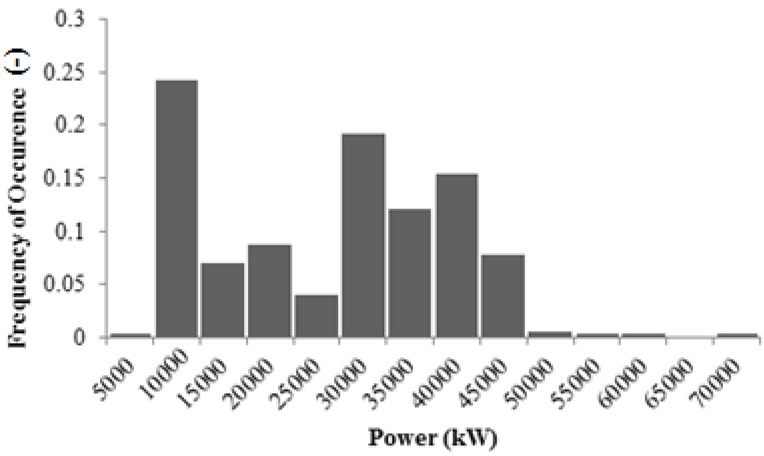

Figure 5: Operational profile of cruise ship

The thermal requirements are expressed as a function of the instantaneous total power demand [58] based on regression performed by using actual operational data collected from cruise ships, according to Equation (3).

$$m_{ss}[\frac{kg}{h}] = -1399\ln(P_i[kW]) + 16295 \quad (3)$$

The investigated alternative technologies for the bi-objective optimisation of the specific case study are summarised in Table 4, including their capital cost derived from the literature or technical reports. The fuel prices employed in the optimisation are the average prices over the first six months of 2018, as displayed in Table 5 along with the lower heating value and the CO_2 emission factor for the considered fuels.

Table 4. List of alternative technologies for the case study

		Capital Cost (€/kW)	**Sources**
Engine types	diesel (D)[2]	490	[59]
	dual fuel engines (DF)[2]	740	[60]
	molten carbon fuel cells (FC)[3]	3500	[61]
Engine fuel type	HFO, LSHFO, MGO, methanol, Natural Gas (NG)		
Thermal boiler type	oil fired	25	[62]
	gas fired (GFB)	25	[62]
Thermal boiler fuel type	HFO, LSHFO, NG		
Energy Efficiency Technologies	Waste Heat Recovery system with Turbo-generator (WHR)[4]	100	[59]
Emission reduction technologies	Exhaust Gas Recirculation (EGR)[4]	80	[63]
	Selective Catalytic Reactor (SCR)[4]	40	[59]
	Exhaust Gas Scrubber[4]	70	[64]
	Carbon Capture System (CC)[1,4]	2600	[65]

[1] *Tank storage of carbon included.*
[2] *Fuel storage and feeding system cost is included.*
[3] *Technology with an internal reformer.*
[4] *Cost per kW of the generator set.*

Table 5: Fuel properties

	Price (€/t)	**Lower Heating Value (LHV) (kJ/kg)**	**CO_2 emission factor (kg CO_2/ kg fuel)**
HFO (IFO 380)	300[1]	39000	3.021
LSHFO (LS380)	350[1]	41000	3.075
Methanol	400[2]	20100	1.375
MGO	590[1]	42800	3.082
NG	250[1]	48600	2.750

[1][66], [2][67]

6. Results

In this section, the bi-objective optimisation results of the investigated cruise ship energy systems for different carbon prices scenarios are presented. The Pareto front solutions derived from the bi-objective optimisation of the LCC and the lifetime CO_2 emissions along with the performance of the baseline configuration are presented for all the scenarios in Figure 6. Each point of the curve describes one optimal configuration according to the set objectives. All the solutions presented comply with the existing IMO regulations for SOx and NOx emissions inside ECA waters as well as the Energy Efficiency Design Index.

The baseline cruise ship energy system configuration, which is installed in the majority of cruise ships of similar size to the one investigated one herein, is shown in Figure 1, whereas its main characteristics are presented in Table 6.

Table 6. Components of the baseline energy systems configuration

Main Engine	Engines number	Nominal power of each engine (kW)	Thermal Boiler	Economiser
Diesel (HFO with LSHFO switch)	6	12000	Oil fired (HFO)	✓

It is obvious from the results presented in Figure 6 that the baseline configuration is not included in the Pareto front of the optimal solutions in any of the scenarios. It is identified that a number of optimal configurations can reduce the LCC and at the same time decrease the lifetime CO_2 emissions more than 40% compared to the baseline configuration. Therefore, it is evident that the bi-objective optimisation method generates a variety of alternative solutions that perform better than the baseline solution in one of the objectives, while some improve the carbon footprint of cruise ship energy systems and at the same time manage to reduce the cost.

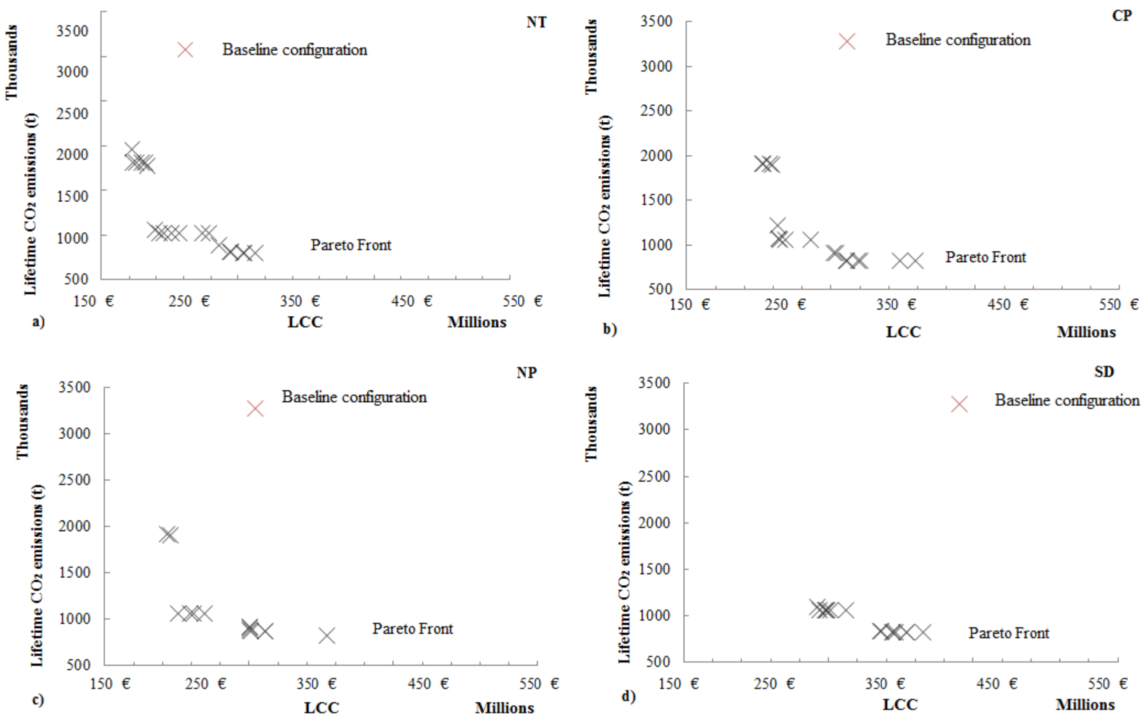

Figure 6: CO_2 & LCC optimisation of ship energy systems: a) NT, b) CP, c) NP, d) SD scenario

Comparing the three first graphs (NT, CP, NP carbon policy scenarios) of Figure 6, it is identified that the solutions of the Pareto front have similar shape, whereas their performance on the lifetime CO_2 emissions objective lie in the range of 700-2000 thousand tons. The solutions differ on the LCC, due to the carbon cost induced by the pricing policies. On the other hand, the solutions on the Pareto front for the SD scenario exhibit a smaller range of CO_2 emissions, which are in the range of 700-1000 thousand tons. This is a consequence of the high cost of the carbon prices and as a result the configurations that emit more CO_2 emissions over the ship lifetime are not optimal any more.

Another observation from Figure 6 is that for the first three scenarios, even though the baseline configuration does not lie on the Pareto front, there are still solutions that perform better than the baseline regarding the CO_2 emissions objective, but have a much higher LCC. However, for the SD scenario all the solutions identified have better economic and carbon footprint than the baseline configuration. This indicates that the higher the expected future carbon price, the less competitive the baseline technological configurations will be in cost terms compared to the ones identified in this work. The Pareto fronts for the different scenarios presented in Figure 6 are discussed in detail in the following figures and tables, where more information is given regarding the configuration of the ship energy systems, in order to highlight the impact of the carbon policy scenarios to the configurations.

To provide a deeper insight on the performance of the baseline configuration under every carbon pricing policy scenario the percentage increase of its life cycle cost is presented in Table 7. As it was expected there is a significant cost increase due to the carbon price and in the extreme situation of the SD scenario the LCC was estimated to be 2.3 times the one of the NT scenario. This finding signifies the importance of identifying alternative technological configurations to avoid the potentially extreme future high life cycle cost impact. In the following paragraphs, the optimal configurations on the four scenarios as derived from the optimisation are discussed in more detail.

Table 7. Baseline configuration LCC for the different carbon pricing scenarios

Scenario	LCC (M€)	LCC variation
NT	213	-
CP	303	+42%
NP	324	+52%
SD	495	+133%

In Figure 7 the solutions forming the Pareto front are analysed and clustered according to the main engine type, where some solutions have the same configuration but different number and size of generator sets. The characteristics of a number of configurations from the optimal Pareto front are displayed in Table 8, where the nominal power and number of the configurations components are presented. The configurations that consist of both diesel and dual fuel generator sets operating with natural gas offer the most cost-efficient solution, due to the low capital cost of the diesel generator set as well as the low cost of the NG and HFO fuels. On the other hand, the solution with the best performance regarding the CO_2 emissions includes fuel cells and dual fuel generator sets operating with NG. The majority of the optimal solutions are configurations with dual fuel engines operating with NG; this is a solution that reduces both the LCC and the emissions. On the Pareto front, there are also solutions that include engines operating with methanol, which offer low carbon emissions due to the methanol low carbon content (half of the one of the natural gas).

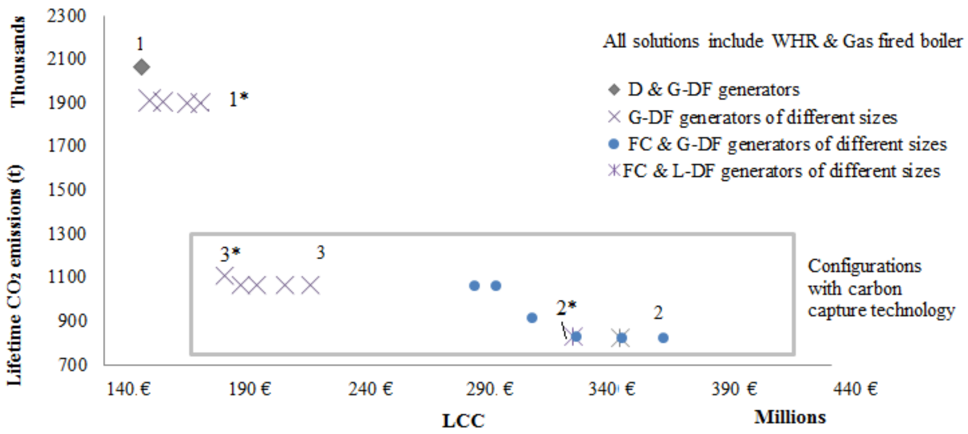

Figure 7: CO_2 & LCC optimal solutions of NT scenario

Table 8. Configurations of Figure 7

	Main Engine Sets / MCR /Type/ Fuel	**Carbon Capture technology**	**Energy Efficiency technology**	**Thermal Boiler**
1	3x7000 kW D (LSHFO) & 4x12000 kW DF (NG)	-	WHR (3000 kW$_e$)	GFB (2x20000 kg/h)
1*	3x12000 kW DF (NG) & 3x11000 kW DF (NG)	-	WHR (3000 kW$_e$)	GFB(2x20000 kg/h)
2	72x500 kW FC (NG) & 3x11000 kW DF (NG)	✓	WHR (3000 kW$_e$)	GFB (2x20000 kg/h)
2*	96x500 kW FC (NG) & 4x6000 kW DF (Meth)	✓	WHR (3000 kW$_e$)	GFB (2x20000 kg/h)
3	3x12000 kW DF (NG) & 3x11000 kW DF (NG)	✓	WHR (3000 kW$_e$)	GFB(2x20000 kg/h)
3*	4x11000 kW DF (NG) & 3x9000 kW DF (NG)	✓	WHR (1000 kW$_e$)	GFB(2x20000 kg/h)

It is also evident that the usage of the CC technology manages to reduce by 40% the CO_2 emissions over the ship lifetime with an increase on the LCC around 20%, comparing the most cost-efficient solution with DF engines to the most cost-efficient solution with DF engines and CC. Another observation is that the WHR technology with turbo-generator is selected in all the optimal solutions, offering both lifetime economic and environmental benefits; despite the increase on the capital cost. In addition, the gas fired boiler dominates all the optimal solutions, due to the fact that the natural gas has lower carbon content and a lower price in comparison with the HFO.

In Figure 8, the LCC of four solutions of the Pareto front is analysed for obtaining a better understanding of the solutions performance. The solutions presented are the optimal ones regarding the economic and CO_2 emissions objectives, the baseline configuration as well as one configuration that belongs to the Pareto front and has similar LCC to the baseline configuration. The configurations of the optimal solutions presented in Figure 8 correspond to the respective numbers shown in Figure 7. From Figure 8, it is inferred that the greatest percentage of the LCC comes from the fuel cost, except for the best CO_2 configuration (solution 2) where the fuel cost is low due to the high efficiency of the fuel cells, whereas the capital and maintenance cost is very high due to the respective high cost of the fuel cells and the carbon capture technology, as well as the replacement cost for the fuel cells stack. Comparing the solution 1 and the baseline configuration, it is evident that the baseline configuration fuel cost is almost three times the fuel cost of solution 1, which combines HFO and natural gas; in addition the maintenance cost of the baseline is higher due to the extra maintenance cost of the emission reduction technologies and the urea required for the SCR system. Solution 3 and the baseline configuration have similar LCC, but the fuel cost of solution 3 is much lower than the baseline configuration fuel cost, whilst on the other hand for solutions 3 there is additional expense for the carbon capture technology.

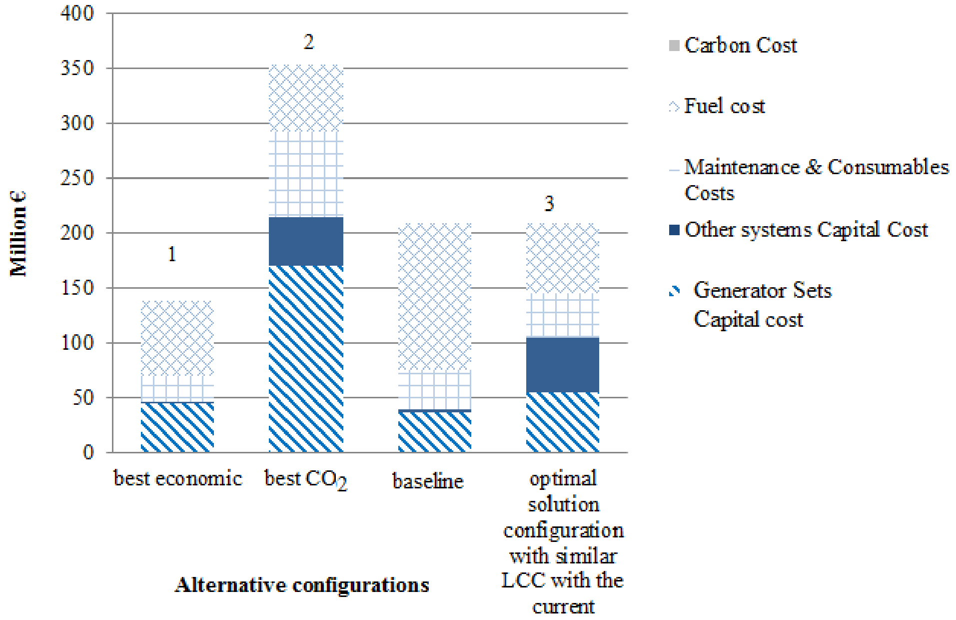

Figure 8: Breakdown of Pareto front solutions of NT scenario

The solutions of the Pareto front for the CP carbon pricing scenario are presented in Figure 9 and a number of these solutions is further analysed in Table 9. The derived configurations are similar to the ones of the Pareto front for the NT scenario. One main difference is that the LCC increased for all solutions due to the higher carbon cost considered in the CP scenario. In addition, the solutions with the best carbon footprint entirely consist of fuel cells compared to the solutions of the NT scenario where dual fuel engines were identified in the optimal solutions. It is inferred from the information presented in Figure 9 that the obtained number of optimal solutions without CC is reduced for the CP scenario. Comparing the most cost-efficient solution with NG with the most cost-efficient with NG and CC in Figure 9, there is a 15% increase on the LCC and 40% decrease on the CO_2 emissions. In comparison with the previous NT scenario, the impact of the carbon cost is quite evident.

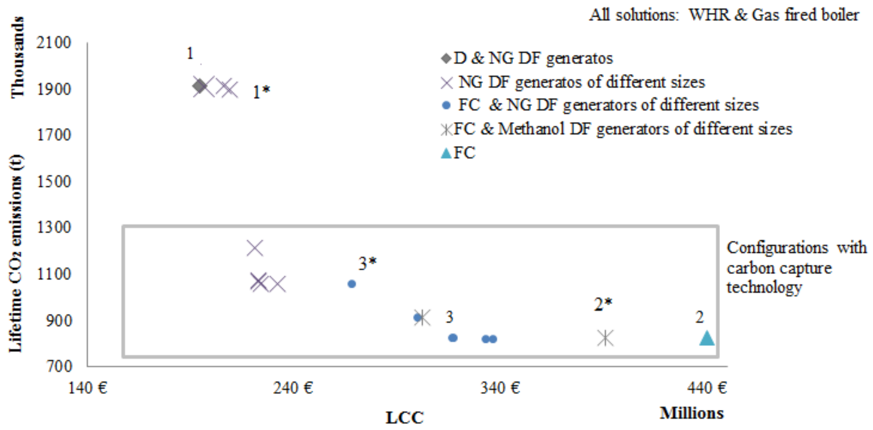

Figure 9: CO_2 & LCC optimal solutions of CP scenario

Table 9. Configurations of Figure 9

	Main Engine Sets / MCR /Type/ Fuel	Carbon Capture technology	Energy Efficiency technology	Thermal Boiler
1	2x7000 kW D (LSHFO) & 4x14000 kW DF (NG)	-	WHR (2000 kWₑ)	GFB (2x20000 kg/h)
1*	4x9000 kW DF (NG) & 3x11000 kW DF (NG)	-	WHR (3000 kWₑ)	GFB(2x20000 kg/h)
2	72x500 kW FC (NG) & 66x500 kW FC (NG)	✓	WHR (3000 kWₑ)	GFB(2x20000 kg/h)
2*	48x500 kW FC (NG) & 4x6000 kW DF (Meth)	✓	WHR (3000 kWₑ)	GFB(2x20000 kg/h)
3	72x500 kW FC (NG) & 3x11000 kW DF (NG)	✓	WHR (3000 kWₑ)	GFB(2x20000 kg/h)
3*	42x500 kW FC (NG) & 4x12000 kW DF (NG)	✓	WHR (3000 kWₑ)	GFB(2x20000 kg/h)

It is derived from Figure 10 that the carbon cost for the baseline solution is two times the carbon cost of the solution 1 and four times the one of the solutions 2 and 3. In the solutions 2 and 3, the configuration consists of fuel cells and carbon capture technology, so this cost reduction was expected. However, from the comparison with the solution 1, it is inferred that inclusion of the dual fuel engines along with the diesel engines reduces the carbon cost to half. It can also be concluded for the baseline solution cost break down that even in the CP scenario, which has the lowest prices for the carbon emissions, the carbon cost over the lifetime of a cruise ship can constitute 30% of the total LCC.

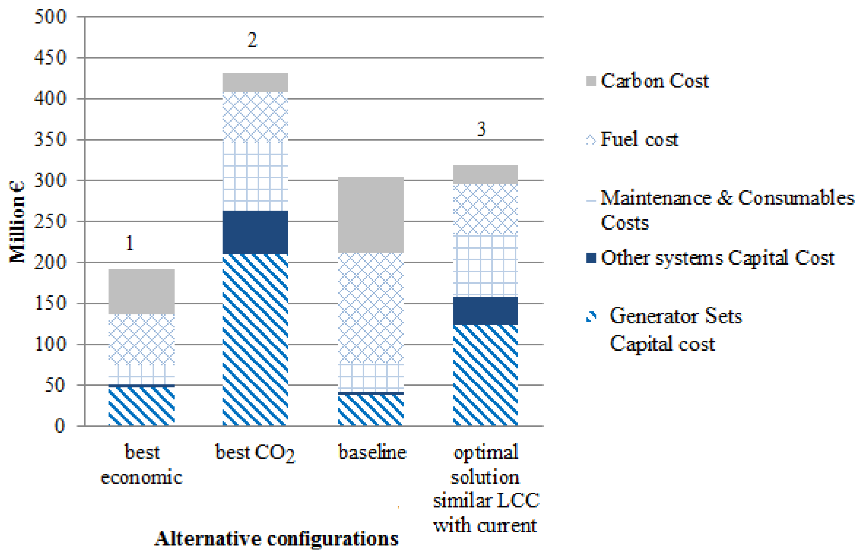

Figure 10: Breakdown of Pareto front solutions of CP scenario

The solutions from the bi-objective optimisation for the NP carbon pricing scenario are displayed in Figure 11 and Table 10. The solutions follow a similar pattern with the ones derived for the CP scenario as the carbon prices for the NP and CP scenarios are close (as shown in Figure 4). Natural gas and methanol fuels are dominant in these optimal solutions. An increase of the LCC is observed compared to the respective LCC of the solutions obtained for the CP scenario. It is also identified that the number of solutions without the carbon capture technology decrease. This is a result of the trade-off between the higher capital investment for advanced CC technologies and the lifetime carbon cost. Comparing the most cost-efficient solutions with NG dual fuel generator sets with or without CC, it is observed a 7% increase on the cost and 40% decrease on the carbon footprint on the latter. As a result, higher carbon price scenarios make the CC technology more favourable as a great reduction of the CO_2 emissions with a small increase on the LCC is obtained.

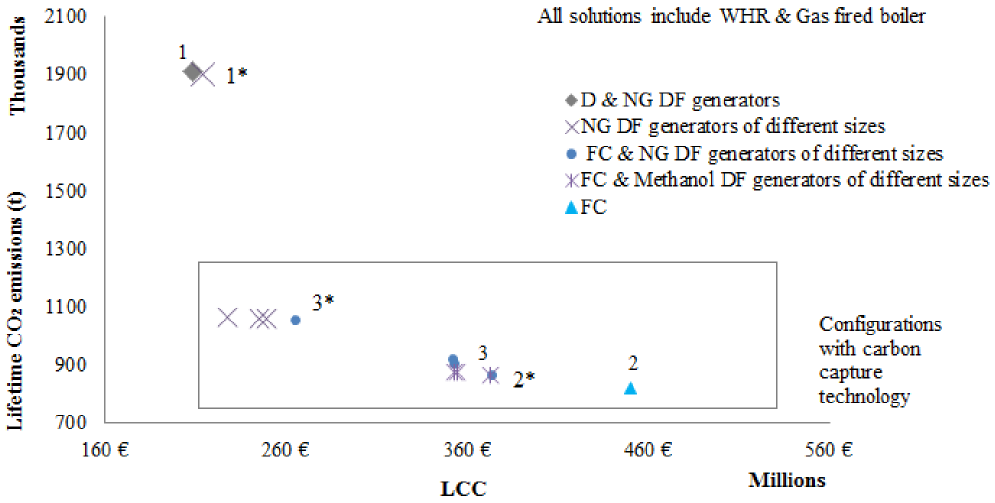

Figure 11: CO_2 & LCC optimal solutions of NP scenario

Table 10. Configurations of Figure 11

	Main Engine Sets / MCR /Type/ Fuel	**Carbon Capture technology**	**Energy Efficiency technology**	**Thermal Boiler**
1	2x7000 kW D (LSHFO) & 4x14000 kW DF (NG)	-	WHR (2000 kW_e)	GFB (2x20000 kg/h)
1*	3x9000 kW DF (NG) & 4x11000 kW DF (NG)	-	WHR (1000 kW_e)	GFB (2x20000 kg/h)
2	72x500 kW FC (NG) & 66x500 kW FC (NG)	✓	WHR (3000 kW_e)	GFB (2x20000 kg/h)
2*	96x500 kW FC (NG) & 4x6000 kW DF (NG)	✓	WHR (3000 kW_e)	GFB (2x20000 kg/h)
3	96x500 kW FC (NG) & 4x6000 kW DF (Meth)	✓	WHR (3000 kW_e)	GFB(2x20000 kg/h)
3*	42x500 kW FC (NG) & 4x12000 kW DF (NG)	✓	WHR (3000 kW_e)	GFB(2x20000 kg/h)

The LCC breakdown for the derived optimal solutions is presented in Figure 12. The configurations are the same with the ones derived for the CP scenario; however, the solution that has similar LCC with the baseline configuration consists of fuel cells and generator sets operating with methanol. It is interesting to compare the second and third solution; the former consists of fuel cells whereas the latter is a combination of fuel cells and dual fuel sets operating with methanol. It is identified that the decrease in the CO_2 emissions and as a result the CO_2 cost reduction is very small; however, the great difference between these configurations is the capital cost in solution 2, which is almost double when only fuel cells are considered. In the NP scenario, where the cost of the carbon increases compared to the CP scenario but still is moderate, it is observed that the carbon cost of the baseline configuration is 30% of the LCC. As a result, a slight increase of the carbon price leads to a 30 M€ increase of the LCC.

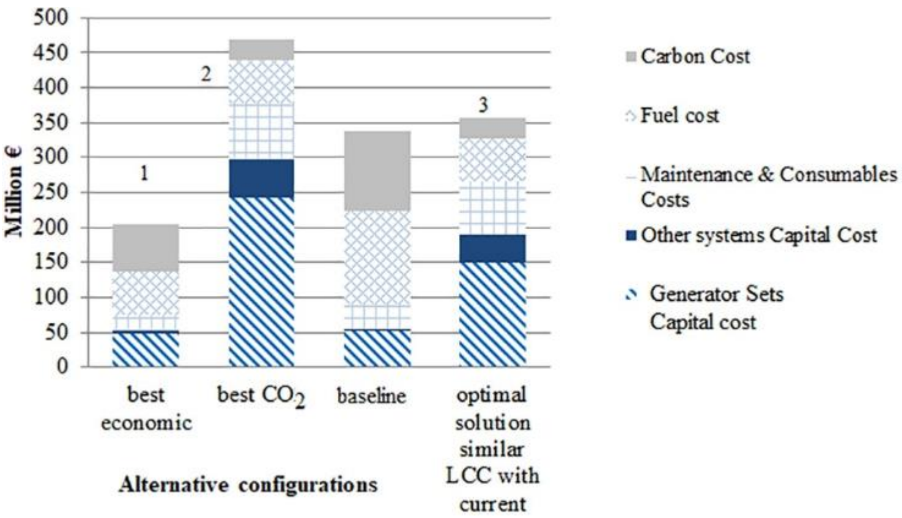

Figure 12: Breakdown of Pareto front solutions of NP scenario

Finally, the Pareto front solutions for the SD scenario are presented in Figure 13 and Table 11. In this case, there is no solution that includes diesel engines, additionally all the optimal solutions include carbon capture. This is due to the fact that the carbon price is very high and the configurations with the lower capital cost in the previous scenarios are no longer optimal due to the higher CO_2 emissions levels and the associated carbon cost. In this scenario, the solution with the best LCC includes dual fuel engines operating with natural gas, gas fired boiler, WHR and carbon capture technology. On the other hand, the one with the optimal CO_2 emissions has similar configuration but it includes fuel cells instead of dual fuel engines. Another configuration that is identified on the Pareto front is a combination of fuel cells with dual fuel engines operating with NG, or with FC and methanol operating DF engines. The percentage of solutions with a combination of fuel cells with dual fuel engines increased, compared to the previous investigated scenarios.

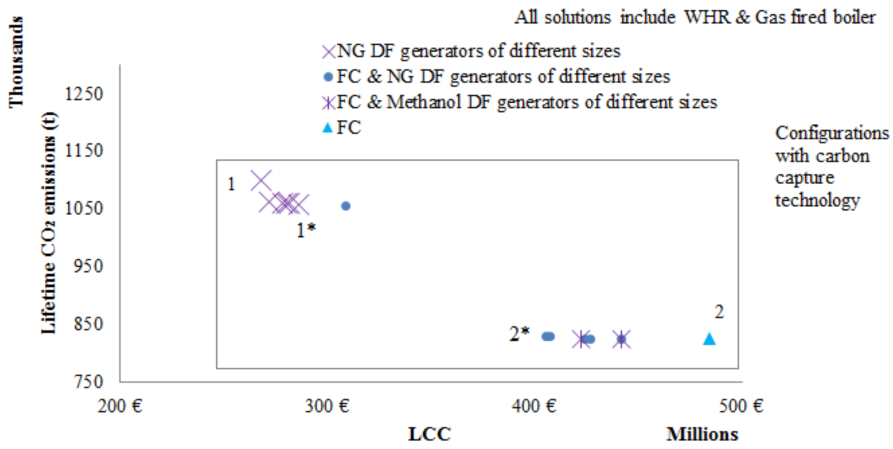

Figure 13: CO_2 & LCC optimal solutions of SD scenario

Table 11. Configurations of Figure 13

	Main Engine Sets / MCR /Type/ Fuel	Carbon Capture technology	Energy Efficiency technology	Thermal Boiler
1	4x11000 kW DF (NG) & 3x9000 kW DF (NG)	✓	WHR (1000 kW_e)	GFB(2x20000 kg/h)
1*	3x12000 kW DF (NG) & 3x11000 kW DF (NG)	✓	WHR (3000 kW_e)	GFB(2x20000 kg/h)
2	96x500 kW FC (NG) & 42x500 kW FC (NG)	✓	WHR (3000 kW_e)	GFB (2x20000 kg/h)
2*	96x500 kW FC (NG) & 4x6000 kW DF (NG)	✓	WHR (3000 kW_e)	GFB (2x20000 kg/h)

The LCC breakdown for a number of solutions for the SD scenario is presented in Figure 14. It can be deduced that there is no solution with a similar cost as the baseline configuration. The solution 2 exhibits the highest LCC and the best CO_2 performance. Due to the very high CO_2 price, the carbon cost constitutes the 61% of the baseline configuration LCC. Comparing with the solutions 1 and 2, the carbon cost of the baseline configuration is approximately three and four times greater, respectively.

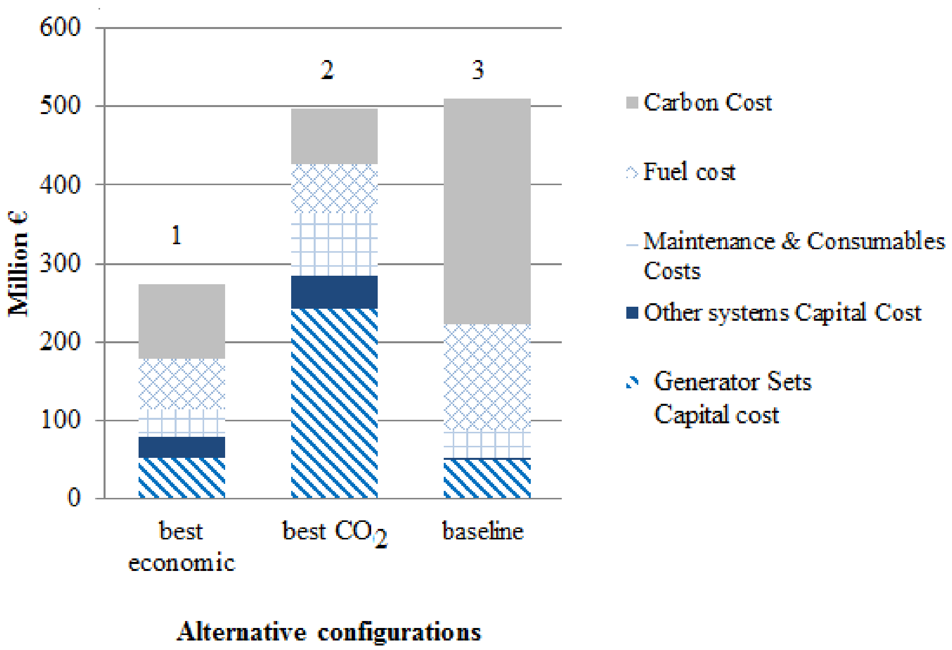

Figure 14: Breakdown of Pareto front solutions of SD scenario

The LCC and CO_2 emissions variations (in comparison with the ones of the baseline configuration) for the optimal solutions with the best LCC and best CO_2 performance for the investigated carbon pricing policy scenarios are presented in Table 12. The LCC values of the solutions discussed in Table 12 are presented in Figure 15.

Table 12. LCC and CO_2 emissions variations in comparison with the baseline configuration of the optimal solutions with the best LCC and the best CO_2 for the investigated carbon price scenarios

	Solution with best LCC		Solutions with best CO_2	
Scenario	LCC variation	CO_2 emissions variation	LCC variation	CO_2 emissions variation
NT	-26.8%	-36.9%	+90.3%	-74.8%
CP	-33.9%	-41.5%	+45.4%	-74.8%
NP	-34.3%	-41.5%	+39.0%	-74.8%
SD	-45.8%	-66.5%	-0.1%	-74.9%

From the results presented in the Figure 15 and the Table 12, it is evident that the solutions derived from the optimisation that perform best in the LCC objective reduce the LCC more than 40% compared to the baseline configuration LCC for all the investigated scenarios. This corresponds to 70 M€ savings for the NT scenario to 200 M€ savings for the SD scenario. In addition to this, it is estimated that a reduction in the range of 37%-66% can be achieved for the lifecycle CO_2 emissions.

The impact of the carbon cost on the LCC is quite significant. For the NT scenario, the carbon cost is zero, as there is no cost for the CO_2 emissions. However, for the solution with the optimal LCC for the CP scenario, the carbon cost is around 54 M€ and corresponding to the 34% of this solution LCC. On the other hand, for the NP scenario where the carbon cost is slightly higher, the CO_2 cost of the optimal solution with the best LCC is 66 M€ and forms the 39% of the LCC. The greatest LCC increase is observed for the SD scenario, where the carbon cost reaches almost 100 M€ and forms more than 40% of the LCC.

For the solutions with the best CO_2 performance, it is inferred that a reduction of the CO_2 emissions more than 70% is achieved, which is attributed to the carbon capture system installation and the usage of the low carbon fuels (natural gas and methanol). In this respect, the proposed configurations facilitate and contribute significantly towards the IMO target for 50% CO_2 emissions reduction by 2050. However, their LCC increases more than 36% in the first three scenarios. Nonetheless, a LCC reduction of 0.1%% (compared to the baseline configuration) is observed for the SD scenario, corresponding to an LCC reduction of more than 50 M€.

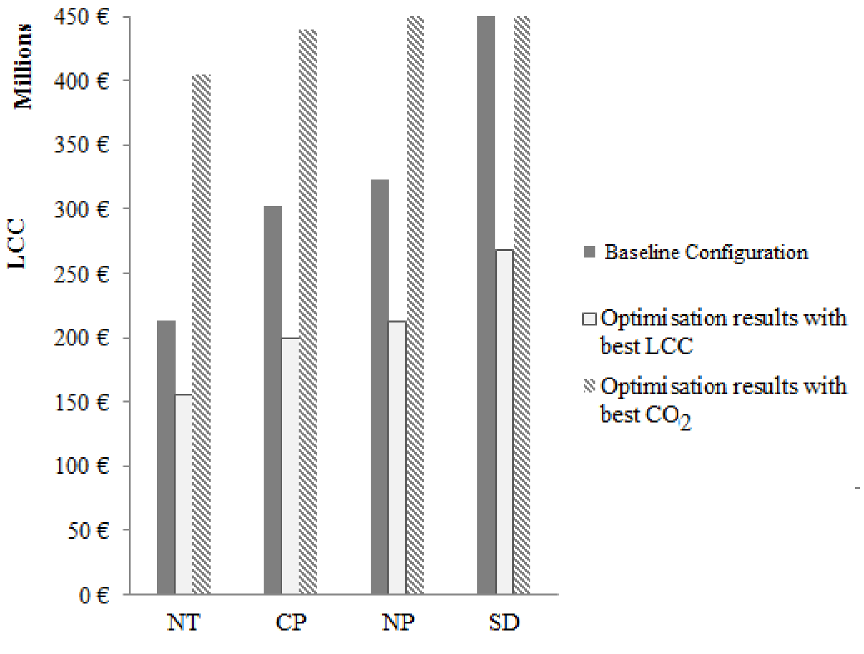

Figure 15: Comparison of LCC of baseline configuration with best LCC and CO_2 optimal solutions

7. Discussion

It can be inferred from the results presented in the preceding section that the most prominent technologies to mitigate the CO_2 emissions whilst reducing the life cycle cost are the technologies operating with natural gas. For the SD scenario, the traditional diesel engines and oil fired boilers operating with HFO exhibited very high operational cost. Despite the fact that the dual fuel engines have a higher capital cost, due to the low carbon content and the low price of the natural gas, these configurations prove to be dominant within the derived optimal solutions. However, in this analysis the life cycle cost included only the capital cost of the generating sets, whereas the cost of the structural changes to accommodate the natural gas storage was not considered.

For the first three scenarios, the solution with the optimal economic performance consists of a combination of diesel engines and dual fuel engines operating with natural gas as well as a gas fired boiler and a WHR system. The fact that these solutions were identified in all three scenarios proves that this configuration is the most cost-efficient alternative, capable to respond to the future carbon pricing policies. In addition, it reduces the lifetime CO_2 emissions more than 30% compared to the baseline configuration. For the SD scenario, which is the highest CO_2 cost scenario, the optimal configuration with the best LCC includes only dual fuel generators operating with natural gas, WHR and CC technology. This configuration in comparison with the baseline one achieves around 67% reduction of the lifecycle CO_2 emissions.

In addition, the generator sets operating with methanol manage to drastically reduce the CO_2 emissions and seem to be a prominent alternative for achieving the CO_2 emissions reduction targets due to the methanol very low carbon content. However, due to the lower methanol heating value (almost half of the one of the natural gas), the fuel storage requirements almost double. Therefore, the fuel storage facilities require a larger size and volume than the respective ones employed for diesel and NG fuels.

Comparing the results of the different scenarios, it is obvious that the percentage of optimal solutions with carbon capture technology drastically increases when the carbon cost increases. This technology exhibits a great potential in reducing the emissions considerably contributing towards the future CO_2 emissions reduction targets, even though it was sized to capture only part of the produced CO_2 emissions due to the imposed space restrictions. It is evident that it manages to reduce drastically the CO_2 emissions, nonetheless the expected increase of the capital cost.

Finally, it was highlighted that the waste heat recovery technology improves the efficiency of the cruise ship energy systems and its benefits surpasses the increase on the capital cost, since this technology was present in each and every solution of the Pareto front, for all carbon pricing scenarios. Therefore, it can be inferred that the WHR technology exhibits a good potential to be included in the future cruise ship energy systems.

8. Concluding remarks

This study explored the optimal cruise ship energy systems configurations to comply with the future carbon pricing policy scenarios. It was demonstrated that the baseline cruise ship energy system configuration does not belong to the Pareto front of the optimal solutions in any of the examined carbon pricing scenarios. The derived optimal configurations regarding the life cycle cost reduced more than 40% of the anticipated costs for the baseline configuration for each scenario whilst reducing the CO_2 emissions more than 37%. It was identified that as the carbon policy scenarios became stricter, the percentage of the carbon cost in the life cycle cost increased, starting from 33% on the CP scenario and increasing to 60% for the SD.

It was inferred that new technologies need to be introduced in the future cruise ship configurations. A combination of diesel and dual fuel engines operating with natural gas is the most cost efficient configuration for the majority of the scenarios. For the most extreme CO_2 cost scenario, the best solution regarding economic objectives included dual fuel engines operating with natural gas. The gas fired thermal boiler and the waste heat recovery technologies were identified in all the optimal solutions. The configurations that manage to achieve the greatest reduction of the CO_2 emissions are the fuel cells combined with carbon capture technology. Finally, the identified solutions with the minimum lifetime CO_2 emissions present a CO_2 emissions reduction more than 70%; contributing the most towards the IMO target for 50% CO_2 emissions reduction by 2050.

In conclusion, the presented method is expected to be a useful tool for assessing the optimal solutions of cruise ships energy systems under various carbon pricing scenarios. In future work even less mature technologies and alternative fuels including hydrogen could be considered in order to investigate their potential to further improve the carbon footprint and the life cycle cost of the future cruise ship energy systems.

Nomenclature

capex	*Capital expenditure (€)*
C_c	*Capital cost factor (€/kW)*
C_f	*Fuel cost factor (€/g)*
C_m	*Maintenance cost factor (€/kWh)*
dr	*Discount rate (%)*
E	*Emissions (g)*
EF	*Emissions factor (g/g of fuel or g/kWh)*
fc	*fuel consumed (g)*
fcc	*fuel cells fuel consumption (g/kWh)*
h	*time (hours)*
i	*set of operational phases i=1..I*
L	*load (-)*
m	*mass flow (kg/h)*
N	*number of components*
opex	*Operational expenditure (€)*
P_i	*instantaneous power (kW)*
P_n	*nominal power (kW)*
sec	*specific energy consumption (kJ/kWh)*
sfc	*specific fuel consumption (gr/kWh)*
t_{CO_2}	*CO_2 emissions tax cost (€/t)*
T	*temperature (^oC)*
Y	*lifetime operations (year)*

Subscripts

ECA	*emission control areas*
ed	*electric energy demand (kW)*
eg	*exhaust gas*

ep *electric energy produced(kW)*
CO_2 *Carbon dioxide*
CC *Carbon Capture*
mpr *minimum power requirements*
n *nominal power (kW)*
ref *reference*
s *energy system*
ss *saturated steam*
td *thermal energy demand (kW)*
th *thermal boiler*
tp *thermal energy produced(kW)*

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Appendix A

The bi-objective optimisation is subject to the following regulatory, power demand related, technical and design constraints.

Regulatory constraints that are mandatory from the maritime regulators:

- The nominal power of the main engine has to fulfil the minimum power requirements according to the regulations and the maximum power requirements of the ship:

$$P_n \geq P_{mpr} \quad \text{(A1)}$$

- The fuel sulphur content has to comply with the limitations introduced by IMO for inside the ECA waters otherwise a scrubber has to be employed:

$$\boldsymbol{S\%_{ECA,s} \leq 0.5\%} \quad \text{(A2)}$$

- The engines have to fulfil the NOx limits Tier II inside ECA waters according to IMO:

$$\boldsymbol{EF_{NOx,s,ECA} \leq EF_{NOx,Tier\ III}} \quad \text{(A3)}$$

- The EEDI value of the ship energy systems has to comply with the EEDI reference value for the specific ship type:

$$EEDI \leq EEDI_{ref} \quad \text{(A3)}$$

Demand-related constraints:

- The operational profile is divided in *I* operational phases and the power demand for each operational phase *i* has to be satisfied for each type of energy vector:

$$\boldsymbol{P_{ep_i} - P_{ed_i} = 0} \quad \text{(A4)}$$

$$\boldsymbol{P_{tp_i} - P_{td_i} = 0} \quad \text{(A5)}$$

Where i=1…I denotes the operational phases.

Technical constraints:

- The incompatibility of technologies is considered and modelled through constraints so that non-compatible technologies are not selected within a single system configuration.

Design constraints:

- The selection of the thermal boilers, in order to cover the adequate capacity of ship operation and comply with the redundancy requirements:

$$\boldsymbol{N_{th} \geq 2} \quad \text{(A6)}$$

Appendix B

The following equations were derived from the regression analysis for the performance of the diesel, dual fuel generator sets and fuel cells:

$$sfc = a_1 L^2 + a_2 L + a_3 \quad \text{(B.1)}$$

$$m_{eg} = b_1 L^2 + b_2 L + b_3 \quad \text{(B.2)}$$

$$T_{eg} = c_1 L^2 + c_2 L + c_3 \quad \text{(B.3)}$$

$$sec = d_1 L^2 + d_2 L + d_3 \quad \text{(B.4)}$$

$$fcc = e_1 L^2 + e_2 L + e_3 \quad \text{(B.5)}$$

The parameters of the regression equations B.1-B.4 for evaluating the performance parameters of the diesel and dual fuel generators are presented in Tables B1 and B2, respectively. The parameters of the regression equations B.5 for evaluating the fuel cells performance are displayed in Table B3. The R^2 values for the developed regressions are also estimated to indicate the regression accuracy. The employed fuel cells units are of the MCFC type and each unit was considered to be 500 kWe. The exhaust mass flow rate is produced in exhaust gas temperature 370°C and the exhaust gas flow rate is considered 0.212 kg/s [68]. The MCFC efficiency is considered 'scale and load-independent' according to [69].

Table B1. Parameters for diesel generators performance

a_1	a_2	a_3	P_n (kW)	R^2=97%
67.24	-118.4	233.2	$3000 \leq P_n < 5000$	
73.07	-124.4	231.2	$5000 \leq P_n < 10000$	
47.64	-90.49	224.6	$10000 \leq P_n \leq 20000$	
b_1	**b_2**	**b_3**	**P_n (kW)**	**R^2=92%**
-2.681	1.817	8.443	$3000 \leq P_n < 5000$	
-4.122	2.747	9.193	$5000 \leq P_n < 20000$	
c_1	**c_2**	**c_3**	**P_n (kW)**	**R^2=99%**
417.7	-664.3	574.5	$3000 \leq P_n < 5000$	
154.4	-238.1	369.7	$5000 \leq P_n < 10000$	
295	-344.8	382.2	$10000 \leq P_n \leq 20000$	

Table B2. Parameters for dual fuel generators performance

d_1	d_2	d_3	P_n (kW)	R^2=94%
24060	-36460	20650	$3060 \leq P_n \leq 6000$	
4145	-7544	10610	$6000 < P_n \leq 20000$	
b_1	**b_2**	**b_3**	**P_n (kW)**	**R^2=99%**
5.186	-9.282	10.16	$3060 \leq P_n \leq 6000$	
-3.112	1.944	8.791	$6000 < P_n \leq 20000$	
c_1	**c_2**	**c_3**	**P_n (kW)**	**R^2=99%**
-45.15	-60.29	461.8	$3060 \leq P_n \leq 6000$	
275	-419.7	437	$6000 < P_n \leq 20000$	

Table B3. Parameters for the fuel cells performance

e_1	e_2	e_3	R^2=96%
6.25	5.75	190.35	