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Reducing the environmental impact of large cruise ships by the adoption of complex cogenerative/trigenerative energy systems

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Abstract

The International Maritime Organization (IMO) has developed new and stricter rules about environmental impact of big vessels. Those rules are going to widen significantly the so called Emission Controlled Areas (ECA) and to generally gain more control over pollution levels over the seas.

The solution that most ship-owners have shown to prefer up to now is be the implementation of pollutant emissions reducing systems, such as Scrubbers and Selective Catalytic Reactor Systems, to dampen emissions produced by the present propulsion systems, based on Internal Combustion Engine (ICE) which burns the cheap but polluting Heavy Fuel Oil (HFO).

An alternative solution, based on the adoption of Gas Turbines (GT) in the propulsion system, fuelled by Marine Gas Oil (MGO), can be taken into account, allowing considerable savings in weight and space occupied and lover NO_x as well as SO_x emissions than those of ICEs, even if with a loss in the engine efficiency [1].

In this paper, the possibility of using simultaneously ICEs and GTs as well as the use of trigeneration system is analyzed, with the aim of exploiting the positive feature of both the engine systems. The paper provides a quantitative comparison among different hybrid engines configurations (ICEs and GTs working together) making reference to a large cruise ship as a real case. Considering a cruise ship rather than a cargo ship implies an important and time-dependent thermal energy demand, so that an onboard trigeneration system may result a convenient solution.

Keywords: IMO; Emissions; Ship energy efficiency; Gas Turbine; Trigeneration systems

Nomenclature

%MCR	Maximum Continuous Rating	[%]
COP_{abs}	Absorption chiller Coefficient of Performance	[-]
DWT	Dead Weight Tonnage	[ton]
$E_{el.}$	Global electric load	[kJ]
E_{fuel}	Fuel energy in a single cruise time interval	[kJ]
$E_{fuel,big,ICE}$	Fuel energy in a single cruise time interval for "big" internal combustion engine	[kJ]
$E_{fuel,small,ICE}$	Fuel energy in a single cruise time interval for "small" internal combustion engine	[kJ]
$E_{fuel,Type\ A,GT}$	Fuel energy in a single cruise time interval for Type A gas turbine	[kJ]
$E_{fuel,Type\ B,GT}$	Fuel energy in a single cruise time interval for Type B gas turbine	[kJ]
$E_{fuel.global}$ (=FE)	Global cruise fuel energy	[kJ]
$E_{fuel.global\_OFBs}$	Global cruise fuel energy for Oil Fired Boilers	[kJ]

$E_{fuel.global\_PMs}$	Global cruise fuel energy for Prime Movers	[kJ]
$El._{chilling}$	Ship electric loads for chilling purposes	[kW]
EF_{ICE_NOx}	ICE’s NO_x emission factor	[g_{NOx}/kg_{fuel}]
EF_{ICE_SOx}	ICE’s SO_x emission factor	[g_{SOx}/kg_{fuel}]
EL	Total electric loads	[kW]
EL_prop.	Propulsive electric loads	[kW]
$E_{TH,ACC.}$	Ship global accommodation thermal load	[kJ]
$E_{TH,FW.}$	Ship global thermal load for fresh water production	[kJ]
FE	Fuel energy content	[kJ]
Fuel	Fuel burned	[ton]
k	Single cruise time interval	
LHV	Lower Heating Value	[kJ/kg]
Non_propulsive	Non propulsive electric loads in the reference case	[MW]
$Non\_propulsive_{Trigen}$	Non propulsive electric loads in the trigeneration case	[MW]
npep	Non-propulsive electric loads	[kW]
$P_{TH,abs.}$	Chilling thermal loads provided by the absorption chillers	[MW]
PE	Pollutant emissions	[g]
t	Integer number of the “smallest” ICE working in the k-th cruise time interval (0, 1 or 2)	
u	Integer number of the “biggest” ICE working in the k-th cruise time interval (0,1 or 2)	
v	Integer number of the “smallest” GT working in the k-th cruise time interval (0,1 or 2)	
z	Integer number of the “biggest” GT working in the k-th	

	cruise time interval (0,1 or 2)	
ΔT_{pp}	Delta T pinch point	[°C]
η	Efficiency	
$\eta_{ship,global}$	Global ship energy efficiency	

Acronyms

A	Autumn
ACC	Accommodation
DeSOx	SO_x abatement devices
DeNOx	NO_x abatement devices
EA	Evolutionary Algorithm
ECA	Emission Controlled Area
EGB	Exhaust Gas Boiler
ER	Engine Room
etTT.. eeET	Hybrid engine configurations with different prime movers
FW	Fresh Water
GHG	Green House Gases
GT	Gas Turbine
HFO	Heavy Fuel Oil
ICE	Internal Combustion Engine
ICE_eco	Internal Combustion Engine in “ecofriendly” mode with SCR and scrubber installed on board
IMO	International Maritime Organization
MARPOL	Maritime Pollution policies

MGO	Marine Gas Oil
MINLP	Mixed Integer Non Linear Programming
OFB	Oil Fired Burners
ORC	Organic Rankine Cycle
PM	Prime Mover
S	Summer
SCR	Selective Catalytic Reactor
SECA	SOx Environmental Controlled Area
TH	Tanks Heating
Trigen	GT engines' configurations with the absorption chiller adoption for chilling purposes
W	Winter

1. Introduction

1.1 Motivation

In maritime transport sector the passenger vessels are undergoing an important development with an increase of about 100% in the last ten years [2]. All ship propulsion systems are fed by fossil fuels therefore, Green House Gases (GHGs) as well as non-GHGs are emitted during ship operation [3]. In the shipping industry, the emission monitoring obligations and standards are regulated by International Maritime Organization (IMO). The Energy Efficiency Design Index and the Ship Energy Efficiency Management Plan are a couple of regulatory actions recently introduced by IMO with the aim of achieving a strong reduction in the GHG emissions. In particular, with respect to the goal of limiting the rise of the global temperature below 2°C, Anderson and Bows [4] have shown that a carbon emission reduction greater than 80% (compared to 2010) has to be achieved from the naval sector.

Since 1973, the environmental impact of ships has been regulated by the International Convention for the Prevention of Ship's Pollution (MARPOL). In particular, in 1997 the "Annex VI," has been added to regulate engine exhaust gas emissions in term of SO_x, NO_x, and particulates [5]. Considering the significant increase in NO_x and SO_x emissions over the last decades [6], the IMO has imposed more and more restrictive emission limits and has identified the need for immediate actions in the more critical areas called SO_x Emission Controlled Areas (SECA). Starting from January 2020, the sulfur content of ship fuel oils will have to be lower than 0.5% in open see and 0.1% in SECA. Since 2016, the MARPOL regulation (Tier III) has prescribed a NOx limit of about 2.5 g/kWh, for medium speed engines. The 2008 revision to MARPOL Annex VI (Annex 13) [7] allow the usage of apparatus or compliance methods as an alternative to low sulfur fuel adoption, if they are at least as effective in terms of emissions reductions as that required by that Annex (regulations 13 and 14).

Because of the new environmental IMO's limits and regulations, ship-owners will have to adopt new strategies and technical solutions in order to cut down both NO_x and SO_x emissions in the marine transport sector.

From a survey among the major ship-owners companies [8], has emerged that two alternatives are nowadays at hand to cut down SO_x emissions: either equipping ships with a $DeSO_x$ system called "scrubber" [9], or substituting the currently used fuel with a sulphur-free one, for instance MGO or Natural Gas. Switching liquid fuel from HFO to MGO would not dispense ships from having to install a specific abatement device to control NOx emissions, even if diesel engines are ongoing a continuous evolution. Selective Catalytic Reactor (SCR) systems are the most frequently used abatement devices thanks to their capability to achieve such a high decrease in NO_x emissions to comply with Tier III NO_X standards [10]. LNG is now considered a good solution to reduce the emissions produced by the propulsion system of a ship for ferries and Ro-Ro [10-12] and the possible convenience of this solution for passenger ships [13] is also evaluated but remain the problem related to important infrastructure to be installed on board, with considerable weight and bulk, in addition to safety problems.

Adopting exhaust gas after treatment devices increases both ship's overall weight and the occupied volume on board. A different strategy for increasing the energy efficiency of the ship propulsion system is the waste heat utilization downstream the ICE [11], such as the integration with Organic Rankine Cycle – ORC [14-16], Rankine [12], Brayton [17], Brayton + Rankine [18] or Rankine + ORC [19]. Unfortunately, all these solutions affect negatively the whole weight of the system and the volume occupation on board, the reduction of which is an important target in the ship design. Therefore, a completely different strategy can be considered like the replacement of the traditional ICE with GTs as prime movers. This solution, which implies a major change of the ship power generation system, involves environmental benefits coming from the use of a Sulphur-free fuel (MGO would be employed instead of HFO) and also from the GT specific combustion system, that allows the NO_x emission level to meet the IMO limits without requiring auxiliary abatement devices. On the other hand, the drawbacks of this solution is the lower energy conversion efficiency of GTs with respect to ICEs, and in the higher cost of the fuel when MGO is used instead of HFO. Very few studies have yet been conducted on the possibility of using propulsion systems based on gas turbines or combined gas-steam cycles [20] for passenger ships, which could be interesting for reducing emissions.

While various studies can be found in literature about land-based energy systems design and optimization, considering different prime mover configurations and waste heat recovery (see, for instance, [21-28]), only few papers can be found dealing specifically with the issue of optimizing non-conventional solutions for the on board energy systems [29-31] for oil tankers applications [32], or in particular for passenger ships [33, 34], with the optimization also of weights and dimensions of the propulsion system [35].

1.2 Previous step of the research

A quantitative analysis has been carried out in the previous study of the present research [1], with the aim to evaluate the positive aspects coming from room and weight savings as well as pollutant emissions reduction against the effective increase of fuel consumption in case of GT employment instead of ICEs. This evaluation is not trivial, since a cruise ship is a closed and complex energy system, its operation profile might be extremely variable, and energy recovery strategies are always implemented in order to reduce the waste heat by partial cogeneration of the thermal demand. For this reason, an optimization strategy has been developed to determine for every cruise time interval, for every engines configurations and for every season, the kind and the number of Prime Mover (PM) switched on, in order to ensure the highest ship energy efficiency.

The results obtained in [1] show that employing GTs as prime movers leads to both environmental and weight and volume benefits, when compared to ICE using HFO, in which De-NO_x / De-SO_x devices have to be added (ICE_eco). Indeed, GTs' emissions of both NO_x and SO_x result to be lower respectively of 85% and 95%, as average, than those of ICE, and comparable to those of ICE_eco. This gap is even wider when emissions of the Oil Fired Burners (OFB) are taken into account. Moreover, a reduction of respectively 11% and 27% in volume and weight vs. the reference case (ICE) is achieved with the employment of GTs. These benefits are even more relevant when the GT case is compared to the ICE_eco, as it has about the double of both weight and volume of the GT.

The drawback consists in the lower energy efficiency of the ship that is obtained as a result of the less favorable electrical efficiency for the GTs and of the greater sensitivity of the latter to seasonal variations of environmental conditions. Therefore, it would be interesting to identify some engine solutions, which could put together the positive aspects of both the ICEs and the GTs.

1.3 Aim of the paper

In this paper, new and not conventional engine configurations, called *hybrid* and characterized by the simultaneous presence onboard of ICEs and GTs, have been considered and the trade-off has been highlighted between the objects of weight/volume requirements, fuel consumption and pollutant emissions, taking into account the new MARPOL regulations. The expectation is that these kinds of not conventional engine configurations could put together the positive aspects of both ICEs and GTs, where the two kinds of engines are simultaneously present on board. Moreover, taking into account that a greater amount of waste heat can be recovered by GTs with respect to ICEs, trigeneration systems can be conveniently employed if GTs are the prevalent kind of engines employed on board, reducing the efficiency gap between the two solutions in term of energy efficiency of the whole ship.

An optimization procedure has been used to quantitatively evaluate the above cited alternative energy production systems, making reference to the real functional data of a modern large cruise ship, sailing along a defined route. The optimization has the objective of minimizing the total fuel consumption, identifying which GT and which ICE has to be in operation, and at which load, in each phase of the cruise. The energy demand in term of heat and electric/propulsion power, as well as the characteristic curve of PM, are the constraints that have to be satisfied during the optimization. Ones the optimal operation has been obtained for a specific not conventional engine configuration, the associated emissions can be calculated and the weight and volume of the whole energy system can be evaluated, allowing a comparison in all these respects.

The results of this analysis can be used as the starting point for economical evaluation of different technologies, taking into account fuel cost and profitable space availability. At the same time the pollutant emissions abatement requirements can be verified to be consistent with the new IMO limits.

2. Complex cogenerative/trigenerative solutions

To evaluate the performance of different complex cogenerative/trigenerative on board energy production systems, as alternative choices to the conventional solution based on ICEs, the case of a specific cruise ship, the vessel C.6194 of Fincantieri S.p.A., has been considered. This cruise ship has 66,000 DeadWeight Tonnage (*DWT*), its standard propulsion system is a diesel-electric and it operates on the route Venice-Barcelona.

As presented in more detail in [1], the whole cruise is described following the three characteristic phases of the cruise ship operation: navigation, port and maneuvering, where the first two take the majority of the operation time; this approach is adopted also in [34] to simulate the energy consumption of a similar type of ship in its operation mode.

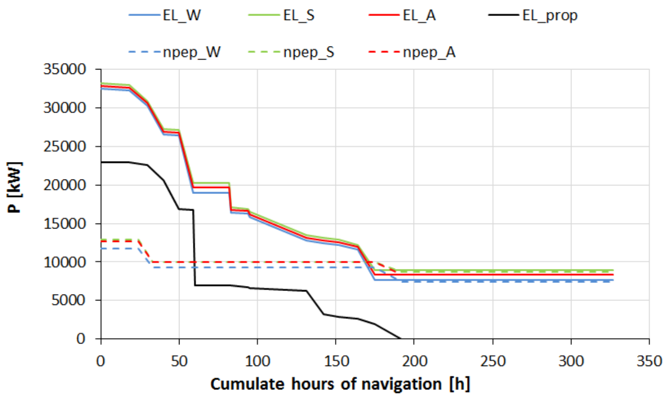


Fig. 1. Duration curves of the electric power demands on reference cruise at different seasons [1].

Figure 1 represents the duration curves of the total electric loads (*EL*). Its main components propulsive (*EL_prop*) (bold black line) and non-propulsive electric loads (*npep*) (dashed colored lines) have been presented separately. The generic cruise was considered for three possible seasons, Summer (S), Winter (W) and intermediate season Spring or Autumn (A), to take into account the different climatic conditions affecting the non-propulsive electric loads. In the modelization, the values of electric and thermal loads have been regarded as constant inside every single one of the 50 time intervals which represent the whole cruise.

The electric consumption of the compression chillers, which satisfy the refrigeration loads in the reference solution, is accounted inside of the non-propulsive electric loads. Thermal loads are divided in two groups depending on the temperature level at which they are fulfilled; high temperature thermal loads are the requirements of the Tanks Heating (TH), the Engine Room users (ER) and the Accommodation service (ACC), whilst low temperature thermal loads are required by the Fresh Water production (FW). The thermal loads, such as the non-propulsive one, depend on the environmental conditions (sea and air temperatures) and therefore different values have been considered for the three typical seasons.

The reference cruise ship loads are satisfied by 4 engines: two big and two small. The engines actually employed on board are ICEs: two Wärtsilä W8L46C and two Wärtsilä W12V46C. In a previous study [1], an alternative engine configuration has been analyzed, replacing ICEs with GTs derived by class Siemens SGT. These two "one-kind" engines solutions display both positive and negative aspects, in terms of fuel consumption, pollutant emissions, weight and volume occupied, as summarized in the Introduction. Then, the object of this study is to consider different engine solutions, putting together the positive aspects of both ICEs and GTs, where the two kinds of engines are simultaneously present on board. In addition, if GTs are the prevalent kind of engines employed on board, trigeneration systems are also considered. All the different system configurations considered are designed to comply with the new IMO emission limits in force from 1/1/2020

Tab. 1. ICE and GT main performance data.

Parameters	**ICE small (8 cyl)**	**ICE big (12 cyl)**	**GT small (Type A)**	**GT big (Type B)**	
Nominal Power	8.4	12.6	8.3	10.6	[MW]

Weight	95	169	30	38	[ton]
Volume occupied	169.5	234	79	81	[m^3]
Exhaust gas flows	14.5	22	26.1	31	[kg/s]
Exhaust gas temp.	340	340	498	545	[°C]
Nominal RPM	514	514	14,010	14,100	[rpm]
η (@100 %MCR)	47.0	47.0	34.6	36.1	[-]
η (@ 90 %MCR)	47.8	47.8	33.9	35.4	[-]
η (@ 80 %MCR)	48.0	48.0	33.1	34.6	[-]

2.1 Hybrid engines configurations

Not conventional engines configurations, called *hybrid* have been considered as a possible alternative energy production system for the reference cruise ship. Adopting simultaneously both ICEs and GTs implies the possibility of combining the low fuel consumption, coming from the use of ICE, with the reduced weight and volume and the great amount of waste heat available in the exhaust gas, typical of GTs.

Several hybrid solutions have been considered. All of them are based on a configuration with 4 prime movers, ICEs or GTs.

Considering all the possible matching between the two available engine sizes (“big” or “small”), the overall number of hybrid solutions considered in the present paper is 13, as summarized in Table 2. In the abbreviation characterizing each configuration, “e” stays for small size ICE, “E” for big size ICE, “t” for small size GT and “T” for big size GT. The presence of an extra 5 MW GT is considered in those engine configurations which have deficit of the total power installed on board of more than 5% with respect to the ICE reference case. This solution allows the exploitation of GT at their maximum efficiency and guarantees the ship navigation safety also in bad see conditions, where an extra power is seldom required.

Tab. 2. Considered hybrid engine configurations.

		etTT	EtTT	ettT	EttT	eett	Eett	eeTT	EETT	eEtT	eEEt	eEET	eeEt	eeET
GT	**Type A**	1	1	2	2	2	2	0	0	1	1	0	1	0
	Type B	2	2	1	1	0	0	2	2	1	0	1	0	1
ICE	**W8L46C**	1	0	1	0	2	0	2	0	1	1	1	2	2
	W12V46C	0	1	0	1	0	2	0	2	1	2	2	1	1
P tot [kW]		38,072	42,272	35,749	39,949	33,484	41,884	38,130	46,530	40,007	41,942	44,265	37,742	40,065
Δ% P tot		-9%	1%	-15%	-5%	-20%	0%	-9%	11%	-5%	0%	5%	-10%	-5%
Extra GT		1	–	1	–	1	–	1	–	–	–	–	1	–
P tot + Extra GT [kW]		43,072	42,272	40,749	39,949	38,484	41,884	43,130	46,530	40,007	41,942	44,265	42,742	40,065
Δ% P tot		3%	1%	-3%	-5%	-8%	0%	3%	11%	-5%	0%	5%	2%	-5%

In hybrid engine configurations, two kinds of fuel are used: HFO and MGO. The former feeds ICEs and OFBs while the latter feeds the GTs. In order to be IMO-compliant, all the ICEs employed on board must have their own exhaust gas after treatment devices, as it has been highlighted by the analysis carried out in [1]. Hence, for each ICE, there is a SCR and a scrubber, which ensure the respect of the IMO limits for NO_x and SO_x. This solution is widely adopted nowadays by ship builders / ship owners to respect the regulatory limits in the short/medium term [36]. A urea injection SCR and a closed loop wet scrubber have been chosen. The SCRs have an abatement efficiency equal to 85% and require 50 kW_{el} [37], while the scrubbers have an abatement efficiency equal to 97% and require 34 kW_{el} [38]. The closed loop wet scrubbers are currently considered the best system to contain SOx emissions produced by naval propulsion systems [9, 39], possibly leading to some restrictions on the washwater discharge within some restricted port area [40]

Thermal loads related to TH and ER users depend on the amount of HFO used on board; therefore, the thermal loads have been determined proportionally to the kind and number of ICE employed.

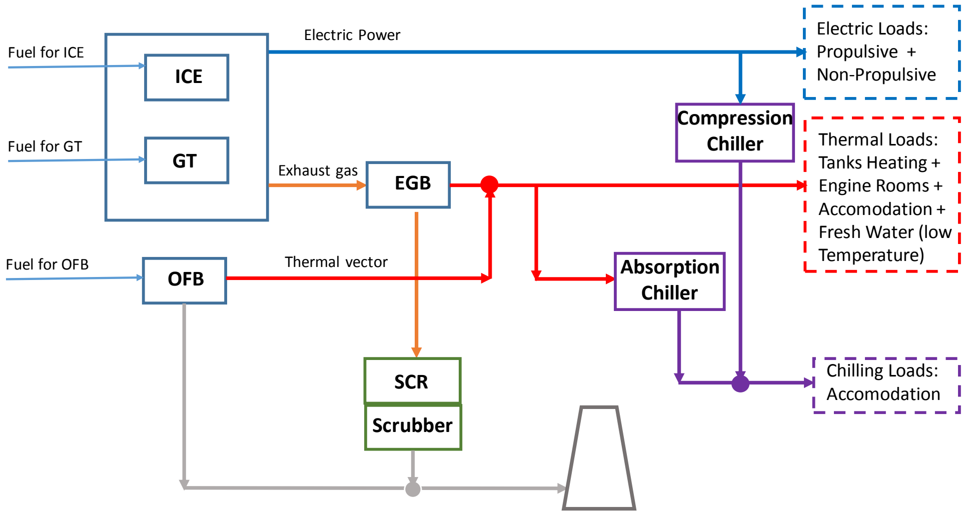


Fig. 2. Schematic model of the cruise ship energy system with trigeneration.

2.2 Trigeneration system

In the reference cruise ship, compression chillers are employed to satisfy the chilling loads, similarly to the conventional land based energy supply systems. Instead of using these devices, absorption machines can be adopted to satisfy the chilling requirements by using an energy recovery from the GT exhaust gas.

From the analysis carried out in [1], it has been obtained that the GT exhaust gas exiting the Exhaust Gas Boilers (EGBs) has a great energy content (about 2.9 10^6 MJ) and a high temperature too (equal to 360°C), therefore, absorption machines can be used effectively. The outcome of this solution is a possible reduction of the gap of global ship energy efficiency between GTs and ICEs configurations which is equal to 10% on average [1].

Recently, several studies on the thermal recovery downstream of the propulsion engines have highlighted the advantage of trigeneration on board [41-44] also as results of optimization of the ship's whole energy system [34]. As an example, in 2012 a cruise ship with a combined system for production of cooling energy for air-conditioning and sea water desalination for drinking water production has been launched [45].

In this paper, this unconventional way of energy production has been named Trigen, and it has been considered for all hybrid engine configurations mainly based on GTs, to exploit the great amount of hot exhaust gases. The model of the ship energy system with trigeneration is shown in Figure 2. The double effect steam driven absorption machine “SD 80A TCU”, produced by THERMAX Inc. [46] has been chosen to define the performance of the trigeneration solutions. It has a cooling capacity equal to 5.1 MW and a $COP_{abs.}$ of 1.4.

Consequently, adopting trigeneration, the ship has lower non-propulsive electric loads as well as higher Accommodation thermal loads with respect to the same ship without trigeneration. The new cruise ship loads are determined by Eq. (1) for Non-propulsive electric loads and by Eq. (2) for Accommodation thermal loads:

$$Non\_propulsive_{Trigen.} = Non\_propulsive - El._{chilling} \qquad [\text{MW}] \qquad (1)$$

$$P_{TH,abs.} = \frac{El._{chilling}}{COP_{abs.}} \qquad [\text{MW}] \qquad (2)$$

where $Non\_propulsive_{Trigen}$ are the new non-propulsive electric loads which refers to the Trigen case, $Non\_propulsive$ are non-propulsive electric loads, $El._{chilling}$ are chilling loads in the reference case, $COP_{abs.}$ is the absorption chillers Coefficient of performance equal to 1.4 [45] and $P_{TH,abs.}$ is the thermal load that has to be provided by the absorption chillers in order to satisfy the chilling loads in the trigeneration case. Eq. (1) and Eq. (2) are valid for each cruise time interval and season. In Table 3 the harbor and the navigation $Non\text{-}propulsive$ and $Non\_propulsive_{Trigen}$ electric loads are reported. It can be noted that the $Non\_propulsive_{Trigen}$ electric loads are the same in all the seasons considered, because of the lack of the chilling compressors electrical loads.

Table 3. *Non-propulsive* and *Non-propulsive*$_{Trigen}$. electric loads corresponding at harbor and navigation phases, for each season considered [MW].

		Non-propulsive		***Non-propulsive***$_{Trigen}$	
		Harbor	Navigation	Harbor	Navigation
Season	W	7.5	9.3	7.2	7.8
	S	8.7	9.9		
	A	8	9.7		

Table 4. Reference and Trigen case accommodation thermal loads corresponding at harbor and navigation phases, for each season considered [MW].

	Navigation			**Harbor**		
	W	S	A	W	S	A
Reference accommodation thermal load	10.8	7.5	6.7	10.8	7.5	6.7
Absorption Chiller ($P_{TH.abs.}$)	4.7	6.7	5.7	0.95	4.8	2.9
Total accommodation thermal load with Trigeneration	15.5	14.2	12.4	11.75	12.3	9.6

The absorption chillers consumption determined by Eq. (2) has to be added to the reference cruise ship thermal loads, as reported in Table 4.

Finally, it must be observed that a bigger total thermal demand, with respect to the reference one, implies a higher steam production from the GT exhaust gas exploitation. This lead to choose bigger EGBs with respect to those selected in the non-trigenerative solutions. In this study, the chosen EGB represent the best compromise between global ship efficiency and the overall occupied volume. The procedure considers the ΔT_{pp} as the main design variable for defining both EGB energy performance and overall occupied volume: 10 different EGBs design configurations have been considered, by choosing different delta T pinch point, varying from a minimum of 34°C to a maximum of 304°C, with steps of 30°C. For each identified ΔT_{pp}, the commercial software THERMOFLEX® [46] has been used to determine all other dependent design data of the EGB, in particular the its heat transfer surface and its volume. Taking into account the different temperature and mass flow rates of the exhaust gases corresponding at each GT electric load, the thermal power production, in off-design conditions too, have been computed. Therefore, the on/off and the load of each GT in a defined propulsion system configuration has been optimized in each one of the 50 time intervals, with the object of achieving the maximum global ship efficiency and the constraints of satisfy all electrical and thermal demands, during the whole cruise. The results are shown in Fig. 3, expressing the optimal annual global ship efficiency vs. the total volume occupied by the EGB, for the 10 design considered, both cogeneration (GT) and trigeneration (Trigen.) configurations. Then, these results suggest that EGB option number 2 is the best solution if trigeneration is considered, while option number 4 has to be regarded as the best compromise for GT case with cogeneration only. In fact, it allows a relevant volume reduction with an efficiency smaller than of 0.5% only.

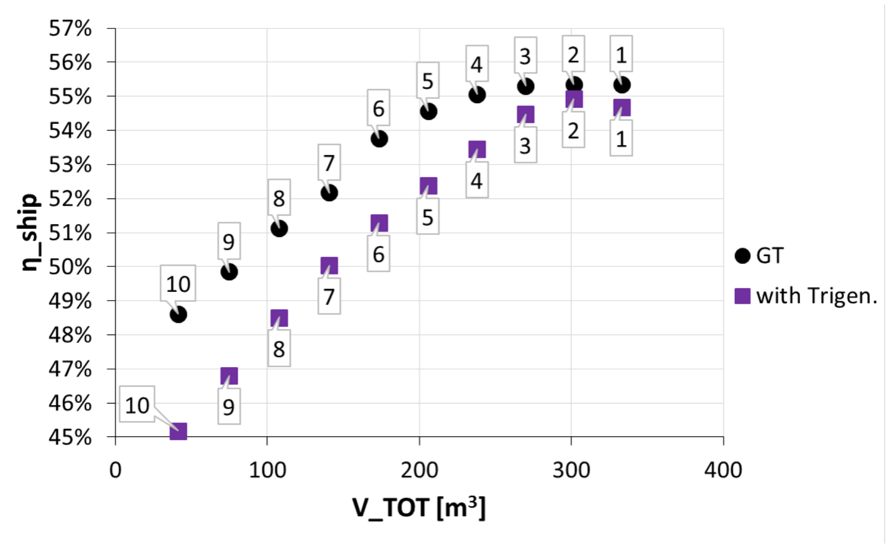


Fig. 3. Annual average global ship efficiency for different selected EGB Vs. the total occupied volume (V_TOT) for GT and Trigen configurations.

3. Methodology

The ship energy system (Fig. 2) has been modeled for all the unconventional engine configurations considered in this paper, where both GT and ICE may be installed on board. First, an energy system model has been defined taking into account the reference cruise operation profile and the performance of the different prime movers described in the previous paragraph. Then, a single objective optimization strategy has been defined for minimizing the global fuel consumption of the ship during the reference cruise, introducing the whole energy system model as a set of constraints.

In the defined optimization strategy, the options regarding the kind (GT / ICE) and size (small / big) of the prime movers are not internal to the optimization, but each one of the 13 hybrid solutions shown in Table 2 has been optimized separately. In this way, the optimization variables represent, for every *k-th* cruise time interval, only the on/off operation of each component of the on board energy system and its running load level.

The defined problem is a Mixed Integer Non Linear Program (MINLP), in fact, it contains both non-linear objective function and constraints, as well as continuous and discrete variables. The solution of this kind of problems is not trivial because the combinatorial difficulty of optimizing over discrete variable sets and the challenges of handling nonlinear functions have to be faced at the same time. In this study, the heuristic approach suggested by Dimopoulos et al. [47] has been chosen.

For each optimal solution of the 13 hybrid engine configurations, the occupied volume and weight of the energy system can be evaluated by the data of the installed components and the emissions of the whole system can be calculated on the basis of their environmental performance in the different optimized operating condition during the whole cruise.

In detail, the optimization has been carried out with the aim of maximizing the global ship energy efficiency $\eta_{ship,global}$, which is determined as in Eq. (3),

$$\eta_{ship,global} = \frac{E_{el.} + E_{TH,ACC.} + E_{TH,FW.}}{E_{fuel,global}} \tag{3}$$

Notice that the ship global electric load $E_{el.}$ (propulsive plus accommodation electric load) and the thermal loads $E_{TH,ACC.}$, for hotel accommodation, and $E_{TH,FW.}$, for fresh water production, depend on the cruise operation profile and not on the optimization variables. Then, by introducing $E_{el.}$, $E_{TH,ACC.}$ and $E_{TH,FW.}$ as additional constraints, in each time interval, the optimization may be reduced to the minimization of the global energy content of the burned fuel both in the prime movers and in the OFBs, $E_{fuel,global}$ Eq. (4):

$$E_{fuel,global} = E_{fuel,global\_PMs} + E_{fuel,global\_OFBs} \qquad [\mathrm{kJ}] \tag{4}$$

For every *k-th* cruise time interval (and for every season) the general optimization statement is provided by Eq. (5):

$$\text{minimize } E_{fuel} = t \times E_{fuel,small,ICE} + u \times E_{fuel,big,ICE} + v \times E_{fuel,Type\_A,GT} + z \times E_{fuel,Type\_B,GT} + E_{fuel,OFBs} \tag{5}$$

constrained by Eq. (6-8):

$$0 \le t, u, v, z \ \le 2 \tag{6}$$

$$E_{fuel,PMs} = f(\%MCR_{PMs}) \tag{7}$$

$$0.5 \leq \%MCR \leq 1 \tag{8}$$

In Eq. (6) $E_{fuel,small,ICE}$ and $E_{fuel,big,ICE}$ are the amount of fuel consumed by the small and big ICE, respectively, whyle $E_{fuel,Type\_A,GT}$ and $E_{fuel,Type\_B,GT}$ are the same consumptions referred to small and big GT, respectively, and $E_{fuel,OFBs}$ is that consumed by the OFBs; t and u are the integer number of the small and big ICE working, v and z are the integer number of the small and big GT working, in the *k-th* cruise time interval (0, 1 or 2). The constraints in Eq. (7) have been expressed by a polynomial approximation of the 3rd order for ICE, on the basis of experimental data from the producer [48], while the characteristic curves of the GTs have been obtained by a model developed with THERMOFLEX® [46]. The Evolutionary Algorithm (EA) option of Microsoft Excel® has been used to solve the single objective optimization procedure of $E_{fuel,global}$. For each *k-th* cruise time interval, the EA has to decide not only which kind of prime movers to switch on, but also how many of that, through the decision variables *t, u, v, z*. In order of obtaining comparable results for all 13 hybrid solutions even if different kinds of fuel, with different *LHV*, are used by ICE and GT, the $E_{fuel,global}$ has been computed in term of energy-fuel content instead of tons of fuel.

A constraint of 0.5 (Eq. (6)) has been imposed to the minimum allowable *%MCR*, in order not to deal with too low engine loads, avoiding a not acceptable increasing of fuel consumption and pollutant emissions.

Then, along with energy efficiency, pollutants emissions are calculated consequently. In particular, five kinds of pollutant emissions are considered: NO_x, SO_x, CO, particulates and HC. Among these, the first two pollutants have been considered the most important because of MARPOL regulations. Only the ICE_eco case includes the pollutant abatement devices. The pollutant emissions by using SCR and scrubber are calculated by:

$$PE_{NO_X} = EF_{ICE\_NO_X} \times Fuel_{ICE} \times \eta_{SCR} \quad (9)$$

$$PE_{SO_X} = EF_{ICE\_SO_X} \times Fuel_{ICE} \times \eta_{scrubber} \quad (10)$$

where EF_{ICE_NOx} and EF_{ICE_SOx} are the emission factors of NO_x and SO_x, respectively, for the ICE using HFO, while η_{SCR} and $\eta s_{crubber}$ are the SCR and scrubber abatement efficiencies, equal to 85%, and 97% respectively [37, 38]. From ABS Advisor for exhaust gas scrubber systems [9] the sulfur content exhaust gas cleaning system emissions equivalence can be inferred. By considering a HFO sulfur content of 2.7 (as mean value for marine HFO fuel [49]), the emission ratio inferred is equal to 117.0 [SO_2 (ppm)/CO_2 (volume %)], therefore, by applying the considered abatement efficiencies, equal to 97%, the emission ratio is reduced to 3.51 [SO_2 (ppm)/CO_2 (volume %)], corresponding to the adoption of a fuel oil with a sulfur content equal to 0,08 %, consistent with the strongest limitation prescribed by IMO (0,1 %). In this way, the adoption of the scrubber abatement system guaranties that the IMO limits are always respected by the ICE_eco solutions and therefore by all hybrid solutions considered in the paper.

4. Results

In the following, the results of the described procedure are reported for the hybrid engine configurations considered and for the Trigen case, as regards the environmental pollution, the ship energy efficiency and weight and volume of the whole energy system.

4.1 Hybrid engine configurations

Results concerning the environmental aspects as well as the energy efficiency for the hybrid engine configurations are reported in Figure 4. The data are normalized with respect to the ICE case. In the

Figure, *FE/FE_ICE* stands for $E_{fuel,global}/E_{fuel,global\_ICE}$, for brevity. The point named "Trigen" will be discussed in the following paragraph 4.3.

Notice that all the hybrid engine configurations are characterized by a strong reduction of both NO_x and SO_x emissions, compared to ICE, and their values are in a very limited range of variation.

For what concern the NO_x emissions (Fig. 4a), hybrid engine configurations allow an average reduction of 75% with a maximum value of avoided emission of 50 tons for the eEET solution.

Considering SO_x emissions (Fig. 4b), hybrid configurations are capable of an even stronger reduction, reaching a decrease of 85% as average, with a maximum value of avoided emission of 56 tons for the etTT and ettT solutions, characterized by only one small ICE.

If hybrid engine configurations are compared to ICE_eco, it can be observed that they behave similarly when NO_x emissions are considered, as a consequence of the SCRs' adoption onboard of all hybrid engines configurations. Taken into account the SO_x emissions, hybrid engine configurations have better performances than ICE_eco, thanks to the partial replacement of HFO with MGO, as well as the presence of scrubbers.

Hybrid configurations cut down also the amount of CO, HC and PM emissions, with respect to ICE case, even if the reduction magnitude is not as high as those observed for NO_x and SO_x. For these kind of pollutants, the calculations show that the configurations with only one ICE lead to the stronger reduction with respect to ICE case, more than 55%, as average.

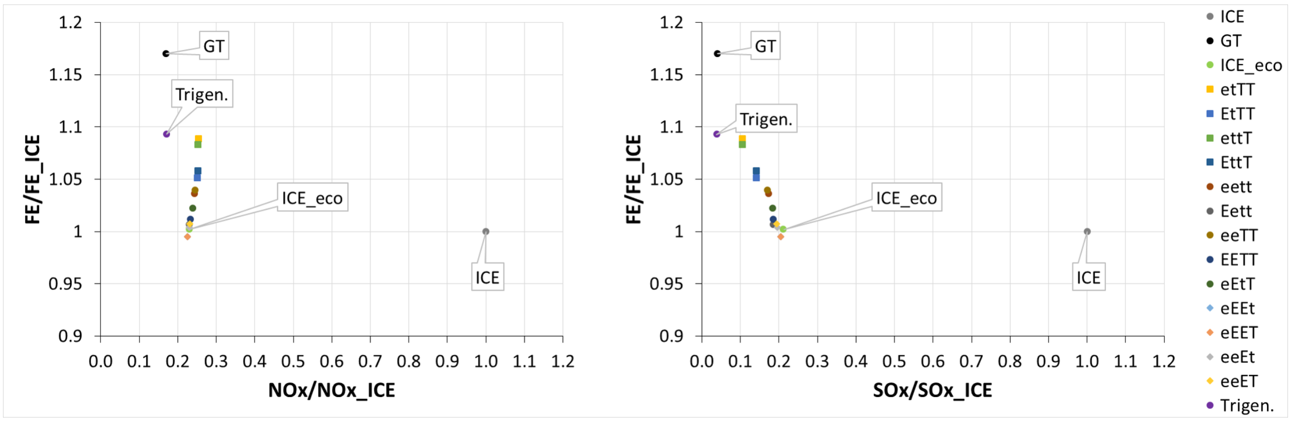
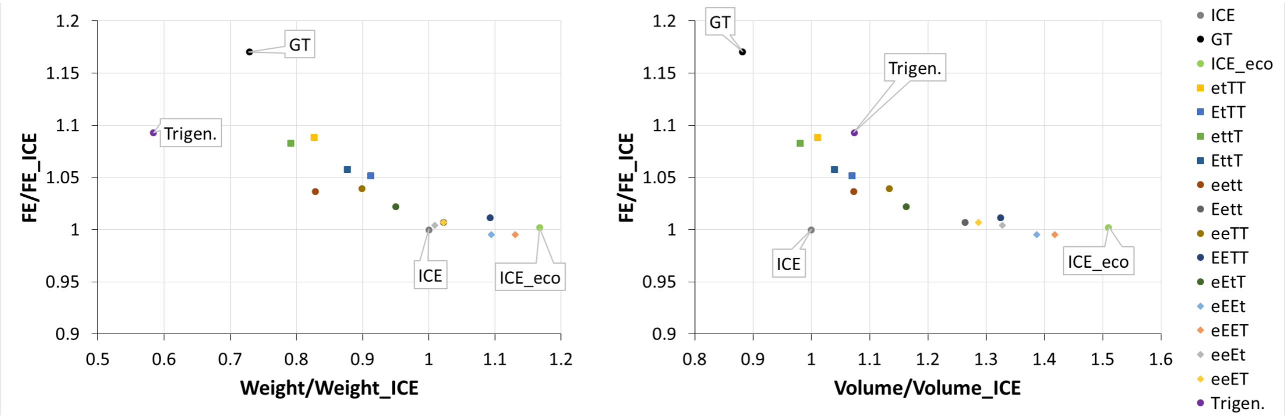

(a) (b)

Fig. 4. FE Vs. NO_x emissions (a) and SO_x emissions (b) for every engine configurations (Normalized with respect to ICE).

On the other hand, satisfying the environmental goal involves a penalty in terms of fuel energy consumptions for the majority of hybrid engine configurations taken into account, as it can be inferred from the analysis of the y-axis in Figure 4. Hybrid configurations show an increase of 5% on average of fuel energy consumptions with respect to both ICE and ICE_eco cases, but a decrease of 12% on average respect to GT case, which can be awarded as the cleanest engine configuration but the most fuel consuming. Notice that the hybrid solutions with only one GT achieve quite the same fuel energy consumption of the ICEs.

Summarizing the results obtained, it can be assessed that:

- Considering the all turbine solution (GT), replacing one small GT with the big ICE, leads to a better fuel energy consumption but to a worse environmental impact;
- Considering the all ICE solution (ICE), replacing one small ICE with a GT, no-matter of which size, allows maintaining quite the same fuel consumption and, at the same time, decreasing the environmental impact.



(a) (b)

Fig. 5. FE Vs. Weight (a) and Volume (b) for every engine configurations (Normalized with respect to ICE).

In the following (Figure 5), the effects on weight and volume variations related to the different options for the hybrid engine configurations are considered. Considering the volume (Figure 5a), a significant reduction is achieved by all hybrid configurations with respect to ICE_eco but only one of them has a volume lower than the ICE, whereas, more options exhibit a weight reduction with respect to both ICE and ICE_eco.

In particular, the best volume reduction option is the case ettT, which is able to reduce the occupied volume of just 2% (-21 m^3) with respect to the ICE case, but it brings a volume increase of 10% with respect to GT case, while the case eEET is the worst one from this point of view, nevertheless it can reduce the volume occupied on board of 6% (-98 m^3) with respect to ICE_eco.

For what the weight reduction is concerned (Figure 5b), all the configurations with one ICE result to be better than ICE case, whilst the configurations with three ICE have higher weight because of the presence of the pollutant abatement devices. In more detail, ettT solution can be considered the best options, with a weight decrease of 21% (-179 ton) when compared to ICE.

In conclusion, if the only solutions consistent to MARPOL limitation are considered and regarding the Figures 5a and 5b as virtual Pareto fronts of a possible multi-objective optimization, the best compromise seems to be the not-dominated solution EEtt, showing a small fuel consumption increment with respect to ICE_ECO, but a significant rduction in both weigh and volume.

4.2 Harbor power management

The environmental performance of the on-board energy systems is especially important during the harbor phase, which is up to the 50% of the whole cruise considered. Thus, besides the option of feeding the ship energy system by an electric cable from the shore (cold ironing) [50], it could be interesting to modify the on board engine operation management when the ship is in harbor. A further analysis has been carried out in order to achieve better environmental performance for the hybrid engine configurations with only one GT, which have shown beter performance in terms of fuel energy consumption.

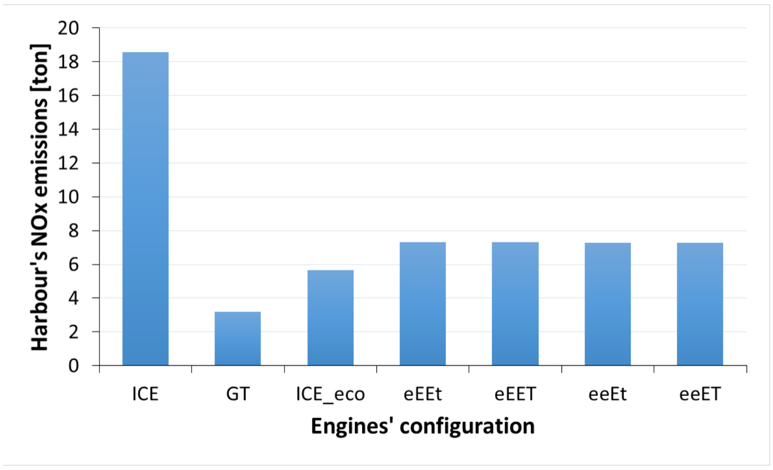


Fig. 6. Annual average NO_x harbor emissions for some engine configurations.

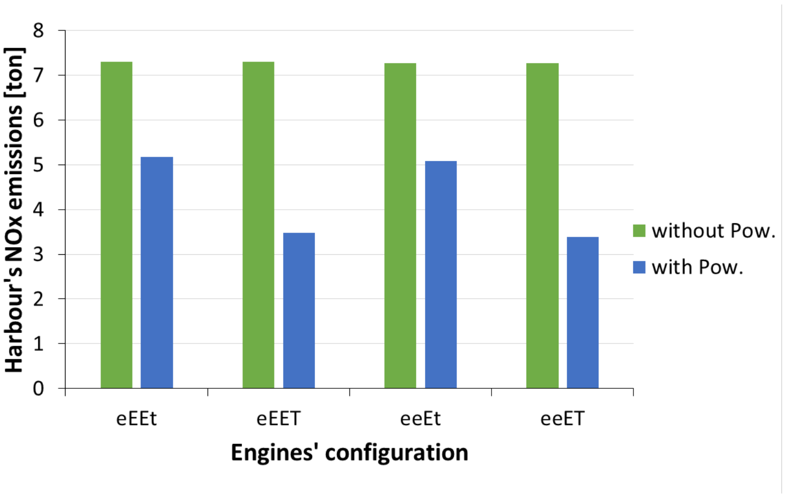


Fig. 7. Annual average NO_x harbor emissions for hybrid engine configurations with only one GT, with and without Power management.

Annual average harbor NO_x emissions, obtained from the previous optimizations, are shown in Figure 6 for ICE class, GT and the hybrid configurations with only one GT. It can be seen that the ship in harbor emits much more in these hybrid configurations with respect to GT case (+100%), but less than +30% with respect to the ICE_eco. For what the SO_x emissions is concerned, the trend is similar, showing about ten times the emission with respect to the GT, and only a +10% with respect to the ICE_eco.

Therefore, it could be interesting to consider a different harbor power management, where the GTs are always switched on in harbor phase. In Figure 7, it can be observed that the use of GT in harbor (Pow) involves a significant reduction in terms of NO_x (30-55%), with respect to the optimal solution for these hybrid configurations. At the same time, the reduction of SO_x is in the range 40-75%. With this strategy the annual average harbor emissions are comparable with those of GT case and even lower than those of the ICE_eco.

As expected, switching on the GT in harbor (Pow) allows achieving such environmental benefits and causes just a little increase of the total fuel energy consumption, equal to 1.4% on average (Figure 8), thanks to the high cogeneration capability of GTs. Then, considering both environmental and energy aspects, it can be concluded that the solution eEET Pow is the best one among all the hybrid engine configurations considered.

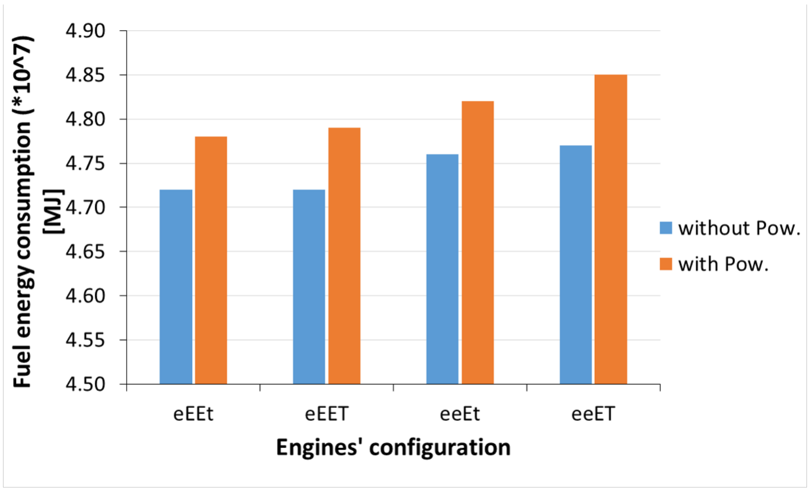


Fig. 8. Annual average fuel energy consumption for hybrid engine configurations with only one GT, with and without Power management.

4.3 Trigeneration

To reduce the gap in terms of global ship energy efficiency between ICEs and GTs, trigeneration systems can be employed on board, enhancing the amount of waste heat recovered by GTs and reducing, at the same time, the total power requirement. In the following, a first comparison is carried out among the previous solutions (GT, ICE, ICE_eco, hybrid) and a Trigeneration system based on GTs only (Trigen case). Afterword, the Trigeneration is taken into account also for hybrid configurations with only one ICE (hybrid_Trigen).

The fuel energy consumption Vs. NO_x and SO_x emissions (normalized with respect to ICE) for the Trigen case has been already shown in Fig. 4, together with all hybrid cases.

Analyzing the y-axis of Figure 4, it can be observed that Trigen case fuel energy consumption is lower with respect to GT case of 7% and it is comparable to that of some hybrid solutions, even if adopting only GTs. The different fuel energy consumption is mainly linked to the following aspects:

- the different way in which the cruise ship thermal loads are satisfied;
- the amount of waste heat released in the environment with the exhaust gas;
- the different non-propulsive electric loads required by compressor and absorption chillers.

The effects of the first two aspects can be evaluated by considering how the annual average thermal load is covered during the whole cruise. Even if the Trigen case has to satisfy a bigger thermal load, the amount of waste heat contained in the GT exhaust gas is so great that a remarkable increase of the OFBs' use is not necessary, but there is less waste heat at the chimney (-10%), with the exit gas temperature decreasing from 287°C for GT case to 129 °C for Trigen case.

For what the non-propulsive electric load is concerned, the lack of compression chillers and the introduction of absorption one, involve a minor electric load to be satisfied. This leads the optimization procedure to choose different kinds of engines to switch on, aiming to provide the most suitable engine combinations with the new waste heat recovery system employed on board.

The different engine combinations result in a lower fuel consumption of the Trigeneration systems, with respect to the GT case.

Considering the pollutant emissions (x-axis of Figure 4), it can be noted that the Trigen case has the same behavior of GT case, as it was expected, achieving NO_x and SO_x reductions of 83% (- 53.5 ton) and 96% (-60.7 ton) respectively, in comparison with ICE. Furthermore, Trigen case provides better results than all the hybrid engine configurations for both NO_x and SO_x emissions. A similar behavior can be obtained for CO, HC and particulate emissions, too.

For what concerns weight and volume (Figure 9), Trigen case is the best option for the weight reduction, i.e. it achieves the half of ICE_eco weight. On the other hand, Trigen case is worse than ICE when the volume is considered. This is because the absorption chillers are lighter but bulkier than compression ones, which are adopted in all the non trigenerative engine configurations.

Considering Trigeneration also for hybrid engine configurations, the more interesting hybrid solutions employs 3 GTs and one ICE with the adoption of absorption chillers in order to recover the great amount of the waste heat contained in the GT exhaust gas. Results concerning the fuel energy consumption Vs. volume and weight for ICE cases, GT cases and four new hybrid solution with trigeneration are reported in Figure 9 (normalized with respect to ICE).

It can be seen that there is a slight reduction in terms of fuel energy consumption when hybrid Trigen solutions are compared to the corresponding ones, without trigeneration. In Figure 10 the annual average percentage of the total thermal load covered by cogeneration is reported for the four hybrid configurations presented in Figure 9, with and without trigeneration.

(a) (b)

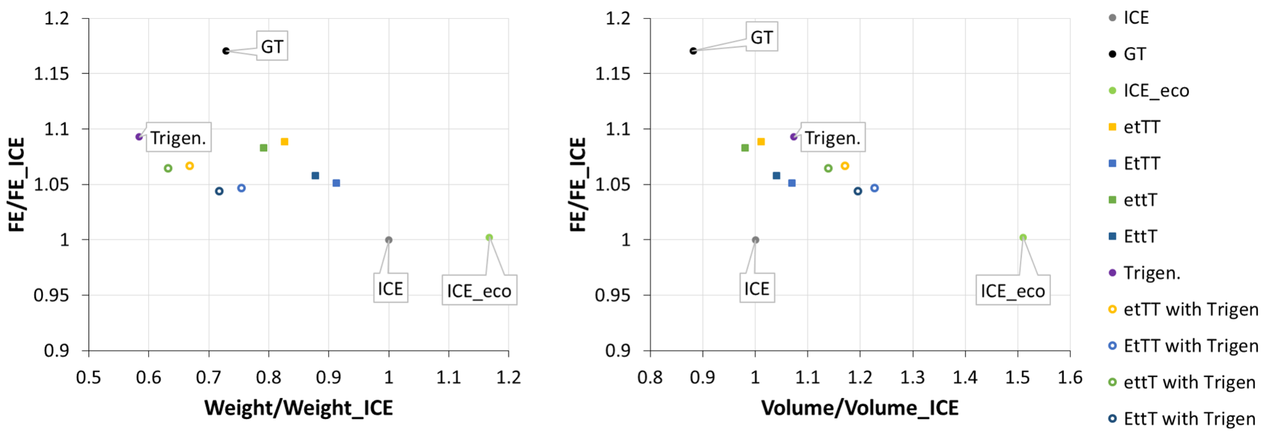


Fig. 9 FE Vs. Weight (a) and Volume (b) for ICE cases, GT class and 1,x Trigen (Normalized with respect to ICE).

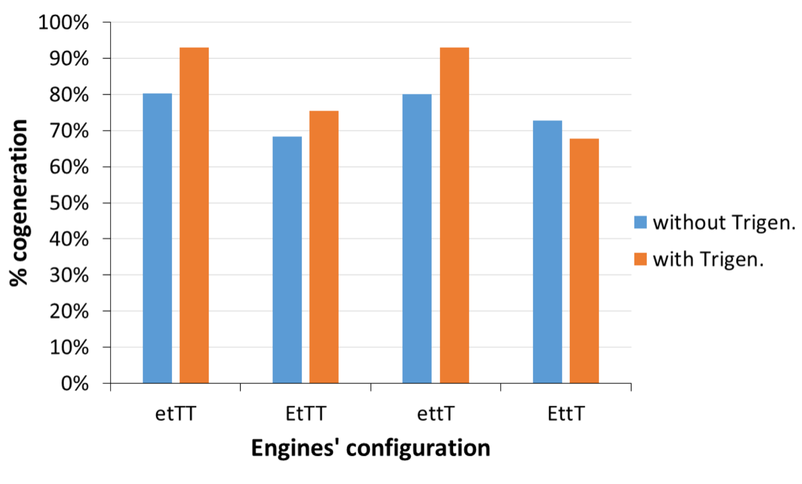


Fig. 10. Annual average thermal load covered by cogeneration for the four hybrid configurations presented in Figure 9, with and without trigeneration.

It can be noted that the introduction of absorption chillers leads to a significant increase of cogeneration percentage for hybrid solutions with the small ICE, etTT and ettT (from 80% to 93%), a slightly increase for the solution with a big ICE and two big GT, EtTT (from 68% to 75%) and a little decrease for the solution EttT (from 72% to 67%). Indeed, the solutions with the small ICE obtain a bigger advantage by adopting the trigeneration system, because the GTs are often in operation, allowing a better exploitation of the waste heat.

5. Conclusions

The present work aimed at quantifying the differences in terms of weight, volume, and fuel consumption of different options for the energy system design of a cruise ship. In order to be compliant with new IMO regulations about pollutant emissions, it is today necessary either to install $DeSO_x$ and $DeNO_x$ abatement systems on the original configuration of HFO fueled ICEs or adopting MGO as fuel. In the last case, GTs may be used for replacing all, or a part of the ICEs, resulting in a hybrid ICE-GT cogeneration system. In addition, trigeneration may be adopted to obtain a better utilization of the waste heat from the GTs.

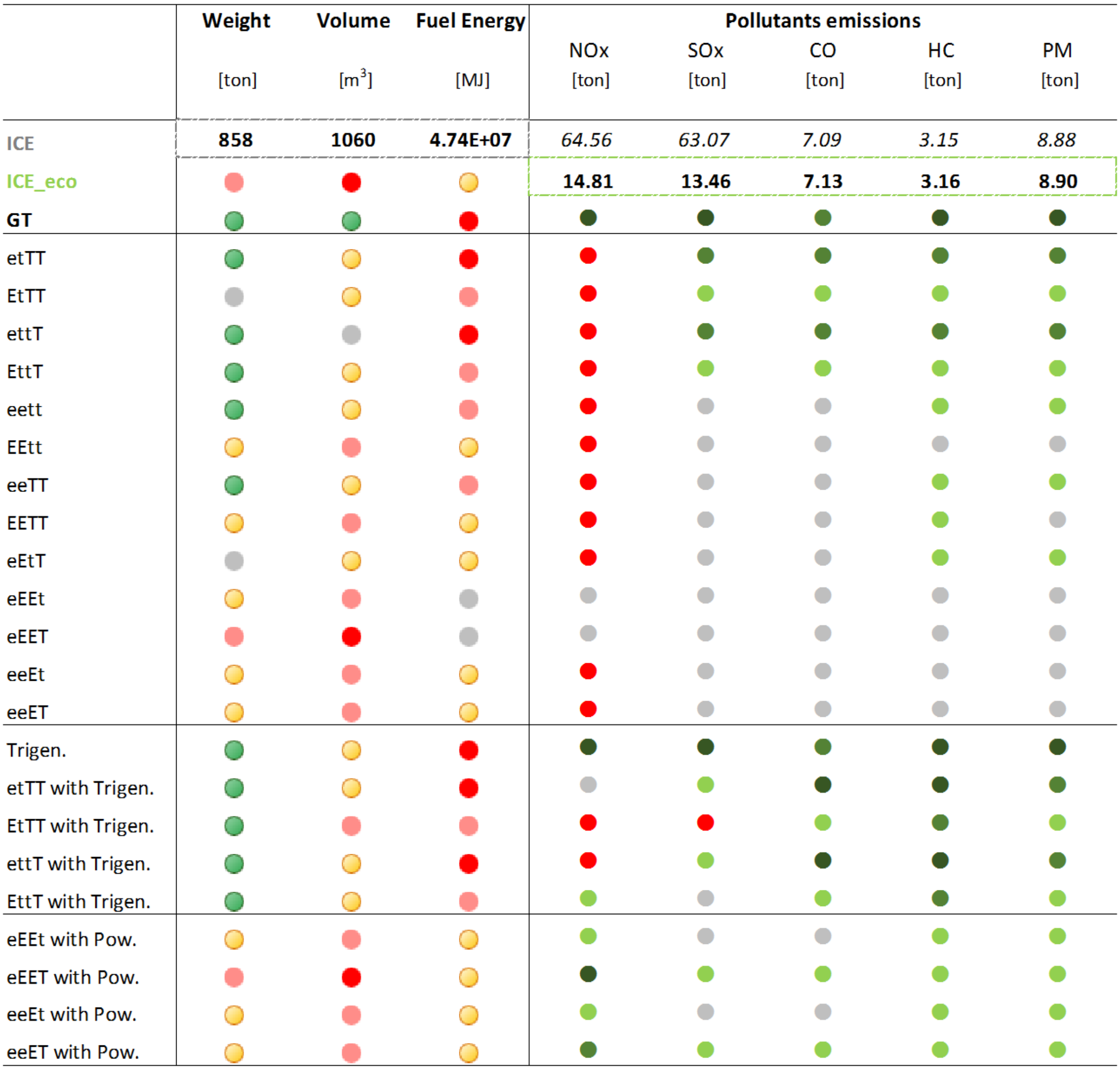
In the paper an optimization procedure has been used to define the optimal design integration and operation of different complex cogenerative and trigenerative energy systems, including both GTs and ICEs. All solutions have been optimized making reference to a large cruise ship sailing on a Mediterranean cruise.

All the quantitative results obtained are summarized in Figure 11 which highlights the different aspects involved by the decisions of the ship-owners and of the maritime sector engineers. The ICE case, which is the actual engine configuration employed on the ship studied, has been taken as reference for weight, room and fuel energy consumption (bold values in Figure 11) meanwhile, the ICE_eco case is considered as the reference (bold values in Figure 11) for the pollutant emissions. This choice has been made because the emissions of ICE_eco are within the limits of the new IMO regulation in force from 1/1/2020.

To allow an easier perception of the different aspects of each solution, a color code has been used instead of numeric values. The variation ranges are different with respect to weight, volume, fuel energy and pollutants emissions as reported in Table 5.

Hybrid configurations generally seem as valid alternatives to configurations based only on one prime mover. In fact, ICE and GT solutions obtain good results in only some of the performance index considered in the analysis, whereas hybrid configurations display good results in several of them. It can be assessed that the most affordable engine configurations are EttT, eett, eEtT, EttT_Trigen and eeET_Pow. In detail:

- EttT, eett, eEtT allow weight reduction, a non-excessive volume expansion, and they also limit fuel consumption with respect to the ICE configuration. Moreover, emissions are better than the ICE_eco, except for NO_x where they go up by an average of 10%, even though still within MARPOL limits;
- EttT_Trigen performs similarly to the same configuration without trigeneration, but it allows even better global results about pollutant emissions;
- eeET_Pow allows to obtain lower emissions compared to the same configuration without power management in harbor, keeping the same increases in weight and volume.



	Weight [ton]	Volume [m³]	Fuel Energy [MJ]	Pollutants emissions NOx [ton]	SOx [ton]	CO [ton]	HC [ton]	PM [ton]
ICE	**858**	**1060**	**4.74E+07**	*64.56*	*63.07*	*7.09*	*3.15*	*8.88*
ICE_eco	🟠	🔴	🟡	**14.81**	**13.46**	**7.13**	**3.16**	**8.90**
GT	🟢	🟢	🔴	🟢	🟢	🟢	🟢	🟢
etTT	🟢	🟡	🔴	🔴	🟢	🟢	🟢	🟢
EtTT	⚪	🟡	🟠	🔴	🟢	🟢	🟢	🟢
ettT	🟢	⚪	🔴	🔴	🟢	🟢	🟢	🟢
EttT	🟢	🟡	🟠	🔴	🟢	🟢	🟢	🟢
eett	🟢	🟡	🟠	🔴	⚪	⚪	🟢	🟢
EEtt	🟡	🟠	🟡	🔴	⚪	⚪	⚪	⚪
eeTT	🟢	🟡	🟠	🔴	⚪	⚪	🟢	🟢
EETT	🟡	🟠	🟡	🔴	⚪	⚪	🟢	⚪
eEtT	⚪	🟡	🟡	🔴	⚪	⚪	🟢	🟢
eEEt	🟡	🟠	⚪	⚪	⚪	⚪	⚪	⚪
eEET	🟠	🔴	⚪	⚪	⚪	⚪	⚪	⚪
eeEt	🟡	🟠	🟡	🔴	⚪	⚪	⚪	⚪
eeET	🟡	🟠	🟡	🔴	⚪	⚪	⚪	⚪
Trigen.	🟢	🟡	🔴	🟢	🟢	🟢	🟢	🟢
etTT with Trigen.	🟢	🟡	🔴	⚪	🟢	🟢	🟢	🟢
EtTT with Trigen.	🟢	🟠	🟠	🔴	🔴	🟢	🟢	🟢
ettT with Trigen.	🟢	🟡	🔴	🔴	🟢	🟢	🟢	🟢
EttT with Trigen.	🟢	🟡	🟠	🟢	⚪	🟢	🟢	🟢
eEEt with Pow.	🟡	🟠	🟡	🟢	⚪	⚪	🟢	🟢
eEET with Pow.	🟠	🔴	🟡	🟢	🟢	🟢	🟢	🟢
eeEt with Pow.	🟡	🟠	🟡	🟢	⚪	⚪	🟢	🟢
eeET with Pow.	🟡	🟠	🟡	🟢	🟢	🟢	🟢	🟢

Fig. 11. Qualitative comparison of all the engine configurations analyzed respect to ICE case, for what concern Weight, Volume, annual average fuel energy consumption, and respect to ICE_eco case for what concern pollutants emissions.

Table 5. Variation ranges of the "Traffic-light" indicators in Figure 11.

Normalized ICE's variations ranges				Normalized ICE_eco's variations ranges			
	Weight	Volume	Fuel Energy		NOx	SOx	Others
●	<0.9	<0.9	<0.99	●	<0.85	<0.25	<0.25
●	0.9-1	0.9-1	0.99-1	●	0.85-0.9	0.25-0.5	0.25-0.5
●	1-1.1	1-1.2	1-1.03	●	0.9-0.95	0.5-0.75	0.5-0.75
●	1.1-1.2	1.2-1.4	1.03-1.06	●	0.95-1	0.75-1	0.75-1
●	>1.2	>1.4	>1.06	●	>1	>1	>1

This means that, for a large cruise ship, the choice to employ GTs as prime movers in hybrid engine configurations, as well as to improve the ship waste heat recovery capability through trigeneration can be of interest. In fact, hybrid configurations allow obtaining, at the same time, good results in all aspects to be considered in the design of the optimal cruise ship energy system. Indeed, they reduce both weight and volume with respect to the ICE_eco case and they are even better from the standpoint of the pollutant emissions, even if with a little increase in the fuel consumption.

The results of this analysis can be used as the starting point for economical evaluation of different technologies which can be adopted on a large cruise ship, taking into account fuel cost and profitable space availability, in order to respect the new IMO exhaust gas emission limits.

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