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Gas Turbines for power generation on board of cruise ships: a possible solution to meet the new IMO regulations?

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Abstract

In order to reduce the environmental impact caused by merchant ships, the International Maritimes Organization is imposing new and stricter regulations on NO_x and SO_x emissions. Therefore, ships propelled by Internal Combustion Engines (ICEs) burning HFO must adopt abatement devices or switch to a cleaner fuel such as MGO. If the use of MGO is considered, a further and more drastic modification of the power system can be analyzed, namely the use of Gas Turbines (GTs) in place of ICEs. GTs are an attractive solution thanks to a reduced weight, size and NO_x emissions, but are penalized by a lower electric efficiency. The case of a real cruise ship is considered in the present paper and a detailed quantification of the above mentioned differences is provided by simulating the ship operation for a reference trip.

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Keywords: Ship Propulsiom, Gas Turbines, IMO, weight reduction.

1. Introduction

NO_x and SO_x emissions produced by merchant ships has been becoming an issue of great concern in recent years. To overcome the problem, International Maritimes Organization (IMO) is imposing stricter rules regarding the environmental impact of large ships. In particular the MARPOL document [1] is setting lower threshold values concerning NO_x and SO_x emissions. Particular attention has been given to sea areas (called SECA) considered to be in need of a more immediate intervention.

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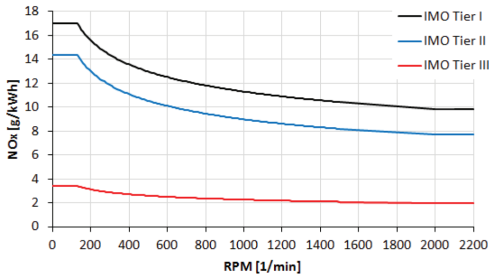


Fig. 1. IMO NO_x limits as a function of ICEs' speed [1].

MARPOL addresses to NO_x pollutants with three Tiers: each Tier consisting in a description of limits imposed on ships in relation to ICEs engine's rpm. Nowadays only ships travelling in the SECA areas have to observe the emission limits of Tier III, but starting from January 1st 2016 every ship will have to (see Tab. 1 and Fig. 1).

Table 1 IMO NO_x limits as a function of ICEs' speed (g/kWh) [1].

MARPOL Tier	RPM<130	130<RPM<2000	RPM>2000
Tier II	14.4	$44 \times RPM^{-0.2}$	7.7
Tier III	3.4	$9 \times RPM^{-0.2}$	2

Regarding SO_x emissions, MARPOL sets limits on the fuel sulphur content differentiating from SECA and not-SECA areas and by defining a severe timeline which lines up a strong lowering of threshold values starting already in 2015 for SECA (see Tab. 2).

Table 2 IMO fuel sulphur content limits [1].

%S content	Area	Year
3.5	Not-SECA	now
1	SECA	now
0.5	Not-SECA	2020
0.1	SECA	2015

As a consequence of IMO regulations, ship-owners will have to adopt new strategies, deciding either on having on-board pollutant abatement systems or switching type of fuel. To cut down SO_x emissions the choice would be between equipping ships with a $DeSO_x$ system ("scrubber") and substituting the currently used fuel with a cleaner one (0.1% S), for instance MGO. Concerning NO_x, even if future evolution of diesel engine's combustion system will allow them to drastically reduce NO_x emissions, at present, the use of specific abatement devices such as SCR is necessary, and the use of MGO in place of HFO doesn't provide an effective solution.

Being saving space and weight a major issue in the ship design process, a different solution could also be considered, namely the use of MGO-fuelled GTs in place of ICEs. Adopting MGO-fuelled GTs means relying on fuel and combustion system characteristics to get pollutant emissions level compliant with the IMO regulations. Moreover, due to the high rotational speed at which GTs are usually operated, the generator paired to them wouldn't be as big as that of an ICE; meaning a further reduction in weight and volume. Finally, as shown in a recent industrial research project [2], these power generation and conversion systems are better suited if coupled with a power grid working in Medium Voltage Direct Current (MVDC), which is an interesting solution currently analyzed for novel cruise ships designs.

As it can be easily foreseen, the drawback of this solution is the negative gap that is found in the energy conversion efficiency of GTs with respect to ICEs', and in the higher cost of MGO compared to HFO. In order to evaluate the technical and economical feasibility of this solution it is vital to be able to quantify the positive aspects

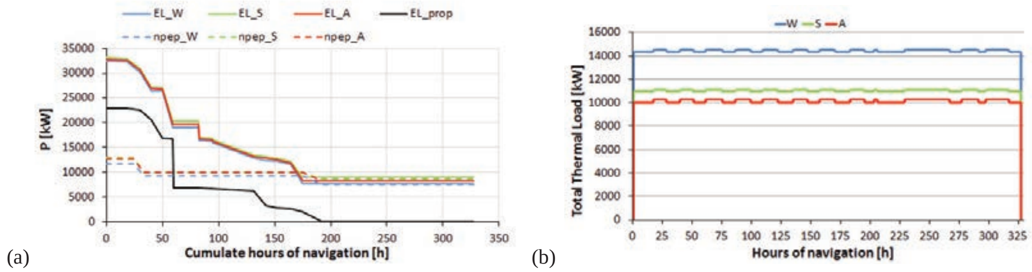


Fig. 2. Seasonal variation of (a) electric (cumulated plot) and (b) thermal loads for the reference ship [3].

coming from room and weight savings against the effective increase in fuel consumption. This evaluation is not trivial, since a ship is a closed and complex energy system, which operation profile might be extremely variable, and where energy recovery strategies are always implemented in order to reduce the waste heat by a partial cogeneration of the thermal loads. With particular regard to this latter aspect, it is also important to consider that, thanks to the high temperature of GTs exhaust gas flows, a higher energy recovery can be achieved, hence reducing the initial efficiency gap between GTs and ICEs intended as prime movers (PMs).

The present paper aims at providing a detailed quantification of the differences in terms of weight, room, fuel consumption and pollutant emissions for the case of a real cruise ship considering three engine configurations:

1. ICE, the current configuration of a Diesel-Electric ship burning HFO and without pollutant abatement devices;
2. ICE_eco, as ICE but with emission abatement devices;
3. GT, a MGO-fueled ship where GTs are used in place of ICEs.

The analysis is conducted by numerically simulating the ship's operation profile during a reference trip, taking as data the evolution of all the electric and thermal loads.

2. Case study

The cruise ship sampled is characterized by a Deadweight Tonnage (DWT) of 66000 tons (about 2100 passengers) and operates on the route Barcelona – Venice. Being ships closed energy systems, PMs are operated in order to satisfy foremost the electric loads. For a Diesel-Electric ship, they are the sum of propulsive load and non-propulsive one (EL_{prop} and EL_{nprop} in Fig. 2(a), respectively). The latter derives from both hotel needs and ship-engine room auxiliaries. The constructor has provided all the data regarding two extreme conditions, namely winter (W) and summer (S), which are also used for design purposes. In order to provide a better analysis about the impact of the seasonal variation on the ship's operation, a further intermediate condition, called autumn (A), has been here defined. Autumn's electric and thermal loads have been computed either interpolating the ones of summer and winter on the basis of mean air and sea temperatures, or just computing their average values.

As it can be seen from Fig. 2(a), only non-propulsive electric loads (EL_{nprop}) show a remarkable seasonal variation that results from the different power consumption of the chiller units. Conversely, propulsive electric loads (EL_{prop}) do not show any seasonal variation but are responsible for the highest differences during the route, ranging from zero (harbour condition) up to 23 MW for the navigation at maximum speed.

The overall thermal power demand reported in Fig. 2(b) results from the sum of two main load classes: the "low temperature", supplied with heat below 100°C; and the "high temperature", covered by the production of steam at 10 bars and 180 °C. The former is mainly linked to the production of fresh water (FW) by multi stage evaporators. The latter instead, results from multiple users which can be divided in three macro-poles: accommodation pole, tanks heating and engine room. Accommodation pole (ACC.) is given by the heating requirements of air (Pre- and Re-heating), sanitary water, swimming pools water, and also galley and laundry services. Tanks heating (T.H.) and engine room (E.R.) poles result instead mainly from the need of keeping the HFO at the required temperature for its stocking and handling.

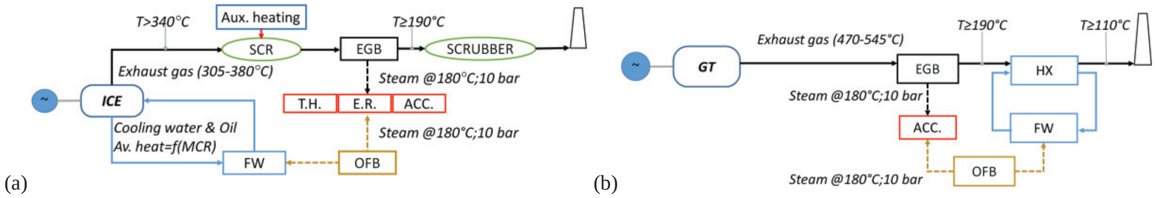


Fig. 3. Cogeneration schemes of the thermal loads for (a) ICE_eco and (b) GT ship configurations.

Figure 3 reports simplified schemes of the adopted solutions for the cogeneration of the above mentioned thermal loads. For the ICE_eco case (Fig. 3(a)) the high temperature loads are satisfied by using Exhaust Gas Boilers (EGB), i.e. recovering the thermal energy of the exhaust gas flows, or , if not enough, by burning fuel in Oil Fuel Burners (OFB) which have a 90% efficiency [3]. The production of fresh water is primarily obtained with the available heat coming from the cooling of the refrigerant water and lubricating oil. Again, OFB can be used to cover the possible negative gap with the actual thermal load. The scheme of Fig 3(a) applies also to the ICE configuration provided that SCR and scrubber are removed. A more simplified configuration can be adopted for the GT case (Fig. 3(b)), indeed only a single stream of hot gases is considered as the available thermal source, moreover no pollutant abatement devices are adopted and the only thermal load is the ACC. Finally, an auxiliary heat exchanger (HX) is installed to provide hot water for the FW production system.

3. Prime movers (PMs)

From the cumulated plot of the electric load in Fig. 2(a), it is possible to highlight the existence of a “base load” condition, i.e. the load value required for the most amount hours. Indeed, it results from the harbour condition of the ship, which consists of 47% of the time. Unfortunately this condition corresponds also to the minimum load requirement that, moreover, is about one fourth of the peak one (8.5 MW V.s. 33 MW). In terms of energy system optimization, this operational condition is quite demanding. In particular it would require either a single engine capable of a very high power modulation with almost constant electric efficiency, or to split the installed power in more and smaller PMs. Actually, the latter is a rather more feasible solution and is also a direct consequence of maritime regulations that force to do so into at least two independent systems. For the present case, the optimization of the choice of the ICEs resulted in a 4 engines configuration, namely two “big” ones of about 12.6 MW (Wärtsilä W12V46C), and two “small” ones of about 8.4 MW (Wärtsilä W8L46C). The resulting modularity allows PMs to operate always (regardless the season and the different phase of the cruise) in a range from 75 to 98% of MCR (Maximum Continuous Rating). It follows that, thanks to the flattened shape of ICE’s efficiency-MCR curve, ICEs work with a mean efficiency of about 45.1 %, i.e. less only than 2% of the peak value of 47.8 % reached for MCR = 87% [4].

In the case of GTs, said solution is even more justified since GTs’s efficiency-MCR curve is steeper than that of an ICE and it is usually characterized by a maximum efficiency at full load condition. For the purposes of the present study, two real industrial gas turbines widely spread into the market have been chosen as a reference (see Tab. 3). These turbines are characterized by a nominal power rather similar to the one of the original ICEs. On the other hand the present electric load evolution would lead them to be always operated at partial load condition, with a severe negative impact on the resulting efficiency. As a consequence, in the present analysis virtual engines have been defined by scaling the original ones, with resulting parameters reported in Tab. 3. Finally, since this way the total power installed would be 38 MW (-9% of that of ICEs configuration) and only for safety reasons, it has been considered to install another GT of 5 MW, hence restoring the total installed power.

4. Pollutant abatement devices

Based on a literature review, SCR with urea-injection and closed loop scrubbers have been chosen as pollutant abatement devices.

Table 3 Characterizing parameters of real GTs and Virtual ones

Parameters	Siemens SGT-300 “Real” [7]	Siemens SGT-400 “Real” [8]	GT-small “Virtual”	GT-big ”Virtual”
Nominal Power [MW]	8.7	13.5	8.3	10.6
Air mass flow [kg/s]	29.99	38.90	28.6	30.5
Exhaust gas flows [kg/s]	26.98	39.28	26.1	31
TOT [°C]	497.7	545.3	497.7	545.3
TIT	1100	1290	1100	1290
rpm	14010	14100	14010	14100
η (100%)	34.65	36.07	34.65	36.07
η (90%)	33.94	35.44	33.94	35.44
η (80%)	33.09	34.62	33.09	34.62

The selected $DeNO_x$ system resulted to be the most suitable for naval applications thanks to its low working temperature (about 340 °C instead of more than 800°C for non catalytic devices) and has been proved to guarantee an abatement efficiency of about 85% [5].

As a further advantage, provided that the exhaust gas is kept above 340 °C, these systems do not suffer from catalyst poisoning effects due to ammonium sulphate compounds. This allows the installation of $DeSO_x$ systems at the end of the exhaust gas line. In this study the use of an auxiliary heat source (OFB) to guarantee the requirement about the gas temperature has been taken into account. The overall electric load resulting from further auxiliaries of the SCR system has been considered to be about 50 kW [3]. Concerning the choice of the $DeSO_x$ system, dry scrubbers have been rejected in view of the disadvantages coming from the need of on-board storage of the cleaning agent (lime products), as well as a storage and shore disposal of used reactant. Regarding wet scrubbers, closed loop solution has been preferred to open loop systems because it results to be more compact, less energy demanding and less dependent on the quality of the sea water. For this solution an abatement efficiency of 97% [6] has been considered and an auxiliary electric load of 34 kW [3] has been taken into account.

5. Results

5.1. Emissions

Figure 4 provides the overall NO_x emissions produced during the cruise for the analyzed configurations and separating the three seasonal conditions as well. Data have been computed relying on specific factors provided by the producers, in particular 12 g NO_x/kWh for ICEs [4] and 15ppmv of NO_x at 15%O_2 for GTs ([7], [8]). A comparison with MARPOL requirements is provided by reporting the threshold values resulting by both Tier II and Tier III limits (dashed lines). In particular, the threshold specific factors for ICEs are directly computed on the basis of the actual engine’s speed (514 rpm), conversely for GTs a lack in the regulations has been highlighted. Indeed, IMO documentation regards only the use of ICEs, therefore, in order to compute a reference limit for the GTs, a conservative choice has been made by considering the lowest values reported in the regulations (i.e. the ones for

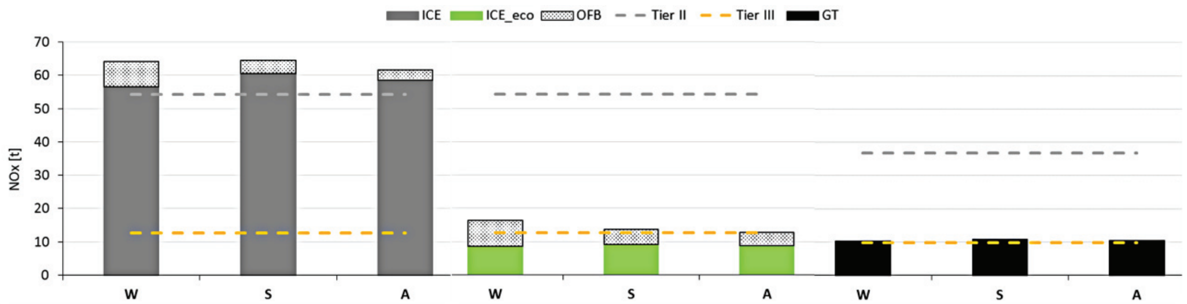


Fig. 4. Overall cruise NO_x emissions.

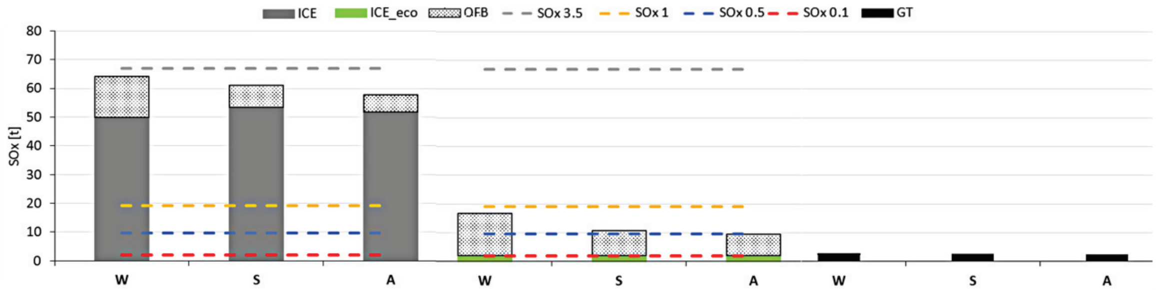


Fig. 5. Overall cruise SO_x emissions.

ICEs above 2000 rpm, see. Fig. 1). The results obtained for ICE case show that the traditional configuration is by far above the limits imposed by Tier III (about +360%) and exceeds also the ones of Tier II even if for a rather small amount. If the latter issue could be easily overcome thanks to the improvements of the combustion systems adopted on modern ICEs, at present, Tier III limits can be reached only by the adoption of SCR systems as done in the ICE_eco case. Conversely, and as expected, GTs NO_x emissions are remarkably reduced, even without SCR devices, and turned out to be comparable to the strict thresholds limits here considered. Moreover, nowadays even lower NO_x emissions factors (about 9 ppmv [9]) can be easily attained thanks to novel Dry Low NO_x combustion systems. In order to make a fair comparison, even if not specifically considered by MARPOL, in the present study also the NO_x emissions coming from OFB have been taken into account. By doing so, the negative gap of ICE case widens considerably, and also for ICE_eco case the limits are exceeded; on the contrary, as it will be clearer hereafter, GT configuration is not affected being the use of OFB rather marginal.

The results about SOx emissions are reported in Fig. 5. Dashed lines indicate MARPOL limits computed on the basis of the different thresholds imposed on the fuel sulphur content (see Tab. 2). The data show that in order to travel through SECA seas, ICE configuration ought to reduce SO_x emissions by at least a 63% average. Said reduction is by far attained by the ICE_eco solution where the scrubber abatement efficiency allows to respect even the stricter future limitations. Thanks to the use of MGO, SO_x emission in the GT case are comparable to the ones of ICE_eco, but they are a little higher than the "SO_x 0.1" threshold level (i.e. the SO_x emissions resulting from ICE burning fuel with 0.1% sulphur content, such as MGO). This issue is a direct consequence of the higher fuel consumption of GTs with respect to ICEs. Finally, regarding Sox, if the contribution of the OFB is added to the PMs, the difference between GT and ICE_eco cases widens considerably, with the latter exceeding also SOx 0.5 limit.

5.2. Efficiency

Figure 6 reports a comparison of cruise averaged values of the ship energetic efficiency (η_{ship}) computed for the three cases and for different seasons and defined as follows:

$$\eta_{ship} = \frac{E_E + E_{TH,ACC} + E_{TH,FW}}{(\dot{m}_{fuel\_PMs} + \dot{m}_{fuel\_OFB}) \times LHV} \quad (1)$$

The numerator of eq. (1) considers only the useful effects, namely the cruise energy demand for electric loads (E_E), thermal accommodation macro-pole ($E_{TH,ACC}$) and fresh water production ($E_{TH,FW}$). Consequently, the energy demand of the auxiliaries has been excluded, such as T.H. and E.R. macro poles and pollutant abatement systems electric loads. At the denominator of eq. (1) $\dot{m}_{fuel\_PMs}$ and $\dot{m}_{fuel\_OFB}$ are the total mass of fuel burned in the PMs and OFBs, respectively, and LHV is the fuel lower heating value.

The highest efficiency is always attained by ICE case. ICE_eco is negatively affected by the supplementary energy demand of the auxiliaries of SCR and scrubber systems that cause a ship efficiency drop of about 1%. Both ICE and ICE_eco cases are only marginally affected by the seasonal changes. On the contrary, GT configuration is rather more sensitive to climate variability resulting to strong variations of the efficiency gap with respect to ICE

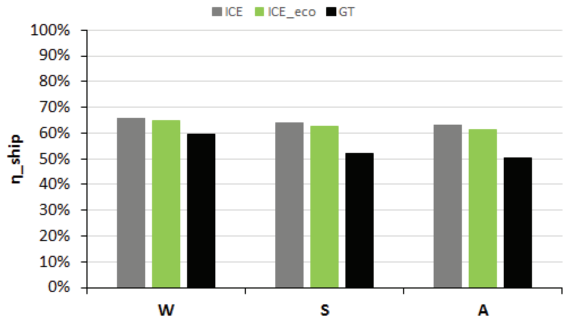
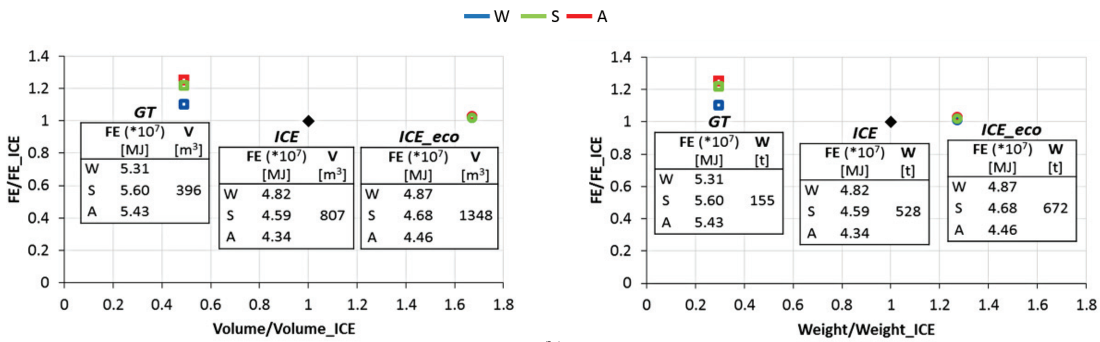


Fig. 6. Cruise-averaged values of the ship energetic efficiency.

case, ranging from –6% for winter up to –13% for autumn. Even if not reported for brevity, it can be seen that thanks to the cogeneration of the thermal loads, the initial gap between the electric efficiency of ICE and GT as PMs can be effectively reduced or even erased as happens for winter-harbour condition. Nevertheless the available heat for GT case often exceeds the thermal ship demand, hence causing a remarkable energy waste that, at the end, results in the observed gap about η_{ship}. The same observation allows also to explain the strong dependence of GT efficiency from seasonal changes, being the thermal loads strictly linked to the climate conditions.

5.3 Weight and volume

The last comparison consists in quantifying the gap existing between all the configurations in terms of room and weight versus the fuel consumption. Given the different LHV of MGO and HFO, the fuel consumption is provided in terms of fuel energy (FE) instead of tons on fuel and it has been computed considering the fuel burned by both PMs and OFBs. The data about weight and room consider the contribution of PMs and pollutant abatement devices, and derive by the technical specifications of the different systems [3,10,11]. In order to ease the analysis, the data reported in Fig. 7 (a) and (b) have been normalized with respect to the values of ICE case, detailed dimensional figures are reported in the attached data labels. The expected room and weight savings consequent to the use of GT is rather clear, with a reduction of respectively 51% and 70% of volume and weight with respect to the current ICE case. The comparison is even more striking if the ICE_eco case is considered. In particular the use of pollutant abatement devices of ICE_eco solution causes an increase of +67% of volume and +27% of weight, so rising the ratio with respect to GT case up to more than three times the volume and more than four times the weight.



(a) (b)

Fig. 7. ICE's Normalized FE Vs. Volume (a) and (b) Weight.

6. Conclusions

The present work aimed at quantifying the differences in terms of weight, volume, and fuel consumption of different designs of a cruise ship that, in order to be compliant with new IMO regulations about pollutant emissions, considers either to install $DeSO_x$ and $DeNO_x$ abatement systems on the original configuration of HFO fuelled ICEs or replacing the current PMs with MGO fuelled GTs. The clear advantage of the latter solution is that, rather than causing an increase of +67% of volume and +27% of weight with respect to the original configuration with ICE only, frees more than 51% of volume and 70% of weight. As expected the lower electric efficiency of GTs causes a drop in the ship energetic efficiency that has been shown to range from -6% for winter climate conditions up to -13% for intermediate sea and air temperatures (autumn). The reason of this variability is linked to the different balance occurring during the year between thermal and electric loads, so that a different beneficial effect is obtained by the cogeneration of the thermal loads. An opposite positive effect linked to the relevant amount of available heat produced by the GTs is that the OFB are used only marginally. Consequently the overall ship pollutant emissions are not affected by the contribution of these devices, conversely to what has been observed for solutions based on ICEs where, if OFB pollutant emissions are considered, MARPOL threshold limits may be exceeded. Finally, considering the strong impact that an effective use of the available heat downstream of the GTs may have on the overall ship efficiency, a further solution based on the combined production of cold and heat (trigenerative systems) may be of real interest for future analysis.

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