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(REVIEW ARTICLE)

Economic and environmental comparison between diesel-electric and mechanical propulsion plants for a small cruise ship

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Abstract

The paper reports an economic and environmental comparison between diesel-electric and mechanical propulsion plants, employed as an alternative to the other one, to the propulsion of a small cruise ship, also described in a previously authors article. The plants prime mover are two versions of the Rolls-Royce Bergen marine diesel engines, employed one as an alternative to the other in all the considered propulsion plants. The engines are characterized by similar rated power but with different power lint curves and specific fuel contours trend in the operating diagram. The diesel-electric propulsion plants are simulated considering the diesel generators working in both constant and variable speed. The economic and environmental (by EEDI and CII index) comparison results, between the considered ship propulsion plants, are presented in tabular and graphical form and commented.

Keywords: Simulation; Diesel-electric propulsion; Marine propulsion plants comparison; Environmental; Economic comparison

1. Introduction

The themes of fuel costs and polluting emissions reduction are of crucial importance in the shipping. The International Maritime Organization (IMO) has established ever more stringent limitations over time on polluting emissions from ships [1-7]. To improve the marine engines efficiency and reduce the fuel consumption, and as consequence the carbon dioxide emissions, the use of electric propulsion has become the norm for cruise ships [8], it is increasingly used also in other types of ships (ie: yachts, ferries and cruise ferries, naval ships) [9-18].

In some ship types, as ferries and cruise vessels, the ship speed can vary significantly during the browsing. This is due the travel schedule and distance between the departure and arrival harbor. In these vessels the propulsion plant engine(s) often works in different conditions to Normal Condition Rating (NCR), that is the one of maximum efficiency of the overall propulsion plant, including propulsion engines and propellers.

The engines operating diagram, power limit-speed curve and specific fuel contours values and trend are more important to the engine and overall propulsion plant efficiency in the different vessel navigation (speed) conditions. In ship mechanical propulsion plants, the engine power limit curve, versus the speed one, influences the propeller operating conditions. The propeller working curve, in the engine operating diagram, must have a trend such as to make the engine operate in conditions of minimum possible specific fuel consumption (*sfc*), respecting the pre-established minimum

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value of the engine margin. To this reason, in these propulsion plants typology, controllable pitch propellers (CPP) are often employed.

In the diesel electric propulsion systems the electric generator fulfill all the ship electric power, required by the propulsion and by the hotel load. As reported in [19] they can operate in constant speed or in variable one. In this last case, the diesel generator engine required power is delivered at the speed corresponding to the lower value of the *sfc* in the engine operating diagram. As reported in [19], another diesel electric propulsion advantage comes from the fact that the propeller speed is independent to the engine one, as consequence, in this propulsion plants for each ship speed, it is possible select the propeller speed that allows the better propulsion system efficiency, and consequently lower fuel consumption and lower pollutant emissions, especially as regard to carbon dioxide (CO_2).

In a previously authors paper [19] was compared, by simulation, the performance of a small cruise ship mechanical and diesel-electric propulsion plants, these lasts in both versions with constant and variable diesel-electric groups, for different ship speeds. All the propulsion system compared in [19] employ, alternately one in place of the other, two Rolls-Royce Bergen engines series, having similar power and speed but different power limit curve and *sfc* contours trend in the engine operating diagram [20].

In this paper the same mechanical and diesel-electric propulsion system, considered in [19] and applied to the same small cruise ship of [19], are compared between them from an economic and an environmental impact point of view, the latter through the EEDI and CII index evaluation.

Chapter 2 of the paper shows the considered propulsion systems layouts, the operating diagrams of the two engines (with the indication of the engines working conditions in the considered types of propulsion system and ship speeds), and the consumption per nautical mile comparisons of the various systems and diesel engines for different vessel speeds.

In the following chapters the different propulsion systems are compared between them from an economic and environmental point of view. The results of these comparisons are presented in tabular and graphical form and commented.

2. Ship, engines and propulsion plants description

2.1. Ship main data

The small cruise ship Spirit of Oceanus, the same studies in [19], is the considered vessel in this article. Tab. 1 reports the main ship propulsion plant data.

Table 1 Main ship data

Overall length	80.7 m
Breadth	15.3 m
Draught	3.9 m
Displacement	3000 t
Gross tonnage	4300 t
Maximum speed (design draught)	18.5 kn
Original propulsion diesel engines	2x2289 kW
Shaft electric generators	2x800 kWe
Diesel generators	2x1050 kWe
Summer hotel electric power	984.7 kW
Winter hotel electric power	727.8 kW
Passenger	120
Crew	72

2.2. Mechanical propulsion plant

The current vessel mechanical propulsion system layout is visualized in Fig. 1, it includes two independent shaft lines, each of them comprises a four stroke diesel engine (MAIN-DE in Fig. 1), a shaft electric generator (SEG), a reduction gear (G) and a controllable pitch propeller (CPP).

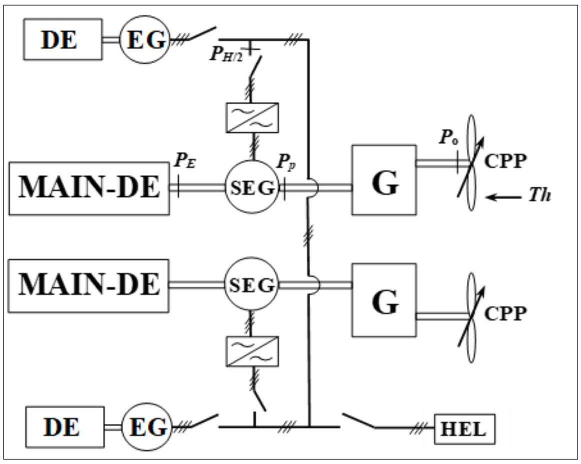


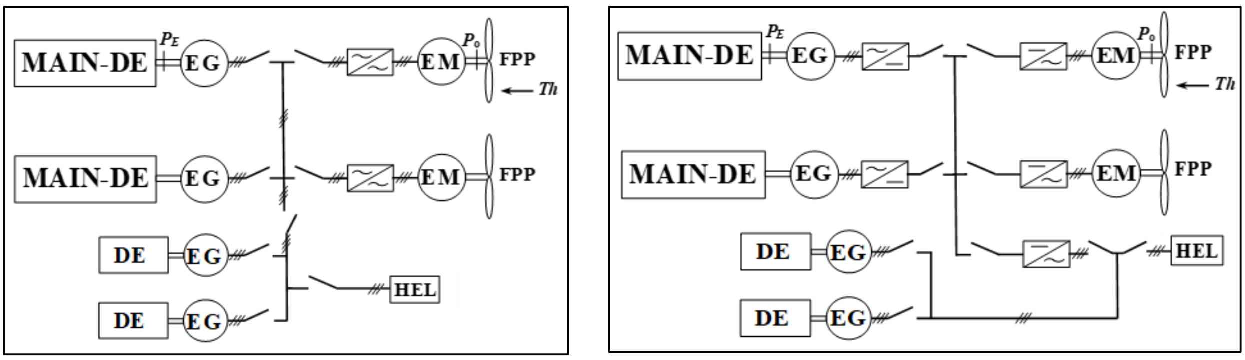
Figure 1 Current mechanical ship propulsion plant layout

Two shaft electric generators (SEG) fulfill the ship hotel electric load (HEL in figure) during the browsing. Two diesel electric generators (DE-EG blocks in Fig. 1) are employed in port.

As reported in detail in [19], the current ship mechanical propulsion plant (Fig. 1) is modelled by the authors in a MATLAB-SIMULINK© modular code. Each module simulates the pertinent plant component (hull, CPP, gear, SEG, MAIN-DE) by correlations and/or tabular data. In [19] the simulator is employed to determine the propeller thrust and power (*Th* and *P*o respectively in Fig. 1) as function of vessel speeds. As reported in [19], through equations that consider each shaft line component efficiency and the hotel electric load, the single MAIN-DE brake power (P_E in Fig. 1) is determined for each ship speed.

2.3. Diesel-electric propulsion plants

As reported in a previous authors paper [20], two diesel-electric ship propulsion plants are conceived for the here considered small cruise ship, a first characterized by constant speed of the diesel-generators, a second with variable one. Figs. 2a and 2b show the respectively system layouts.



a b

Figure 2 Diesel-electric system layouts, with constant speed electric generators (a) and variable one (b)

In both system schemes the MAIN-DE engines fulfill both the propeller power and the hotel electric one (P_o and HEL respectively in Fig. 2). Similarly to the mechanical propulsion plant (Fig. 1), also in diesel-electric systems the two diesel electric generators (DE-EG in Fig. 2) are used in harbor.

For the reasons explained in [20], both the diesel-electric plants use fixed pitch propellers (FPP in Fig. 2) instead of controllable pitch propellers employed in the mechanical one (Fig. 1).

Similarly to what was done for the numerical modelling of the mechanical propulsion system of Fig. 1, also the two diesel-electric propulsion systems of Figs. 2a and 2b were modelled by two MATLAB-SIMULINK© modular codes, described in detail in [20]. Also in these codes, by equations that take in to account each system component efficiency and plant layout, for each vessel speed the single MAIN-DE brake power (P_E in Figs. 2a and 2b) is calculated.

2.4. Main diesel engines

Similarly to what done in [19,20], the propulsion engines currently used in the cruise ship propulsion plants, are substitute with analogue power and speed four-stroke diesel engines type of Rolls-Royce Bergen C25:33L8P series [21], declined in two different maximum rotational speed (900 and 1000 rpm of maximum speed (N_{MAX})), whose main data are reported in Tab. 2.

Table 2 Engines main data and Maximum Continuous Rating performance parameters

Engines parameters	**RR C25:33L8P 900 rpm N_{MAX}**	**RR C25:33L8P 1000 rpm N_{MAX}**
Cylinder numbers	8	8
Bore	250.0 mm	250.0 mm
Stroke	330.0 mm	330.0 mm
Brake power	2560 kW	2665 kW
B.m.e.p.	26.4 bar	24.7 bar
Maximum speed	900 rpm	1000 rpm
Norm. MCR *sfc*	1	1.005

In Tab. 2: RR means Rolls-Royce, b.m.e.p. is the brake mean effective pressure, MCR is the engine Maximum Continuous Rating, the 'Norm. MCR *sfc*' is the engine MCR *sfc* normalized by dividing to the RR C25:33L8P 900 rpm N_{MAX} MCR load condition value one.

Fig. 3 shows the RR C25:33L8P diesel engines power limit curves and *sfc* contours reported in their operating diagram, Fig. 3a for the 900 rpm N_{MAX} engine and Fig. 3b referred to the 1000 rpm N_{MAX} one. Fig. 3 data are normalized as in Tab. 2.

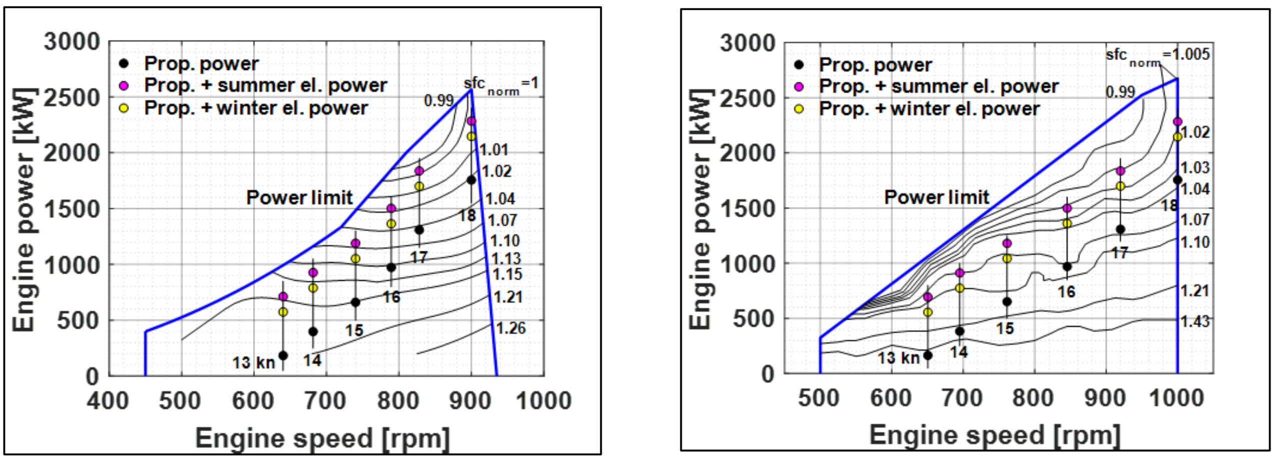


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Figure 3 900 (a) and 1000 (b) rpm N_{max} Bergen engines normalized *sfc* contours and mechanical propulsion plant working conditions vs ship speed on engines power-speed plan

The different power limit curves and *sfc* contours trend between the two engine versions are evident in the figure, these differences are commented in [19].

Applying the calculation procedure described in [19] for the mechanical propulsion plants, the working conditions of each of the considered Bergen engines can be determined, as function of the vessel speed, reported in the respective engine load diagram in Fig. 3; where the black markers indicates the propulsion power only, the magenta and yellow markers represent the overall power (propulsion plus hotel power) required to the engine in summer (magenta) and winter (yellow) browsing.

As regard of the diesel-electric ship propulsion systems, Fig. 4 shows the 900 rpm N_{MAX} (Fig. 4a) and the 1000 rpm N_{MAX} (Fig. 4b) engines working conditions of the diesel-electric plants with diesel-generators operating at constant (plant scheme of Fig. 2a) and variable speeds (plant layout of Fig. 2b), referred summer navigation and to all the considered ship speeds. In the Fig. 4 the red numbers indicate the active diesel generators number (MAIN-DE in Fig. 2), depending by the sum of the propulsion ad hotel required power. The engines working conditions reported in Fig. 4 are determined with the procedure described in [20]. With the same procedure are defined the engines working conditions, reported in Fig. 5 in both diesel generators constant and variable speed of Fig. 2, in winter browsing.

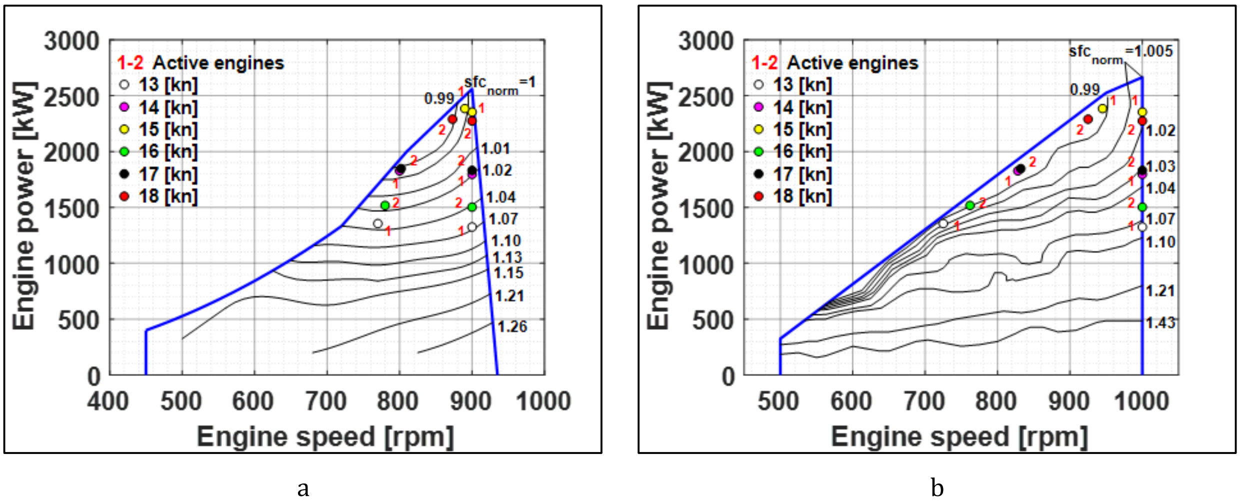


Figure 4 900 (a) and 1000 (b) rpm N_{MAX} Bergen engines normalized constant *sfc* contours and constant or variable diesel-generators speeds diesel-electric propulsion plants in summer working conditions vs ship speed on engines power-speed plan

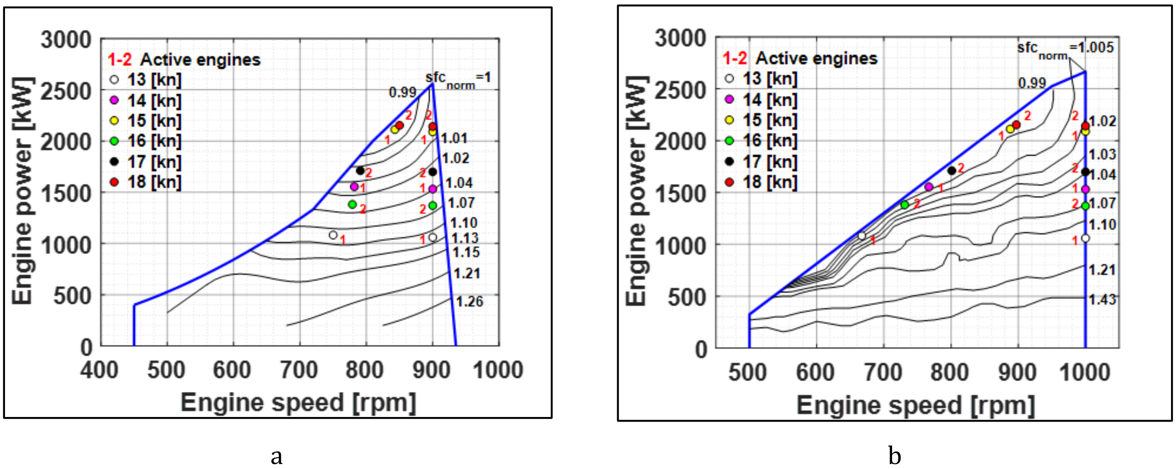


Figure 5 900 (a) and 1000 (b) rpm N_{MAX} Bergen engines normalized constant *sfc* contours and constant or variable diesel-generators speeds diesel-electric propulsion plants in winter working conditions vs ship speed on engines power-speed plan

3. Propulsion plants technical comparison

The technical comparison between the propulsion plants is carried out for sundry ship speed values, included in the 13-18 knots range, with one knot step speed. For the comparison, only the essential data for this article purposes are considered, while a more complete technical comparison between the different propulsion systems is reported in a previous authors paper [20].

3.1. Diesel electric propulsion plants comparison

The comparison of the engines operating diagram between the summer navigation (Fig. 4) and the winter one (Fig. 5), put in evidence that, to ship speed and engine type parity (900 rpm N_{MAX} (Fig. 4a) and 1000 rpm N_{MAX} (Fig. 4b)), MAIN-DE delivered power is greater in the summer browsing, due its greater electrical hotel power, as shows in Tab. 1. This fact is observed both in the systems with diesel generators operating at constant speed (DG-cs) in Fig. 2a and in those with variable one (DG-vs) in Fig. 2b).

Figs. 4 and 5 shows that, to the same engine type, ship speed and season, the MAIN-DEs overall power of the propulsion plant with DG-vs is always higher compared to that of DG-cs one, this difference increase in summer navigation. This fact is due to the higher number of voltage and frequency conversion systems in the DG-vs plants, compared to the DG-cs one (see Figs. 2b and 2a respectively). The MAIN-DEs overall power difference increases as the ship's speed decreases, because to the vessel speed reduction the ship's hotel load power percentage increases.

In all the considered diesel-electric propulsion plants typology and engines, from a ship speed of 15 knots downwards the MAIN-DEs active goes from two to one (see Figs. 4 and 5). This because from ship speed 15 knots to descend the mechanical total power required by the propellers and hotel load is less than the single MAIN-DE maximum power.

Fig. 6 reports the vessel nautical mile fuel consumption (m_f) comparison between the diesel-electric propulsion plants with DG-cs and DG-vs. The data reported in this figure are calculated by:

$$\Delta m_f / m_f\,\% = \frac{m_{f\,DG-vs} - m_{f\,DG-cs}}{m_{f\,DG-cs}} 100\ [\%] \quad \text{.......... (1)}$$

with: $m_{f\,DG-vs}$ and $m_{f\,DG-cs}$ the ship nautical mile fuel consumption referred to variable speed and the constant one diesel generators respectively.

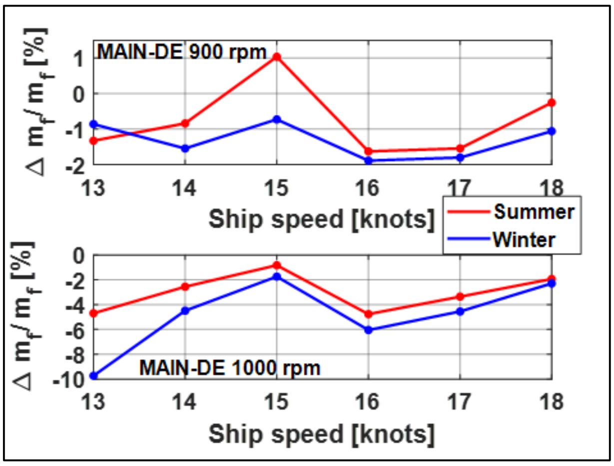


Figure 6 DG-vs plants vs DG-cs one 900 and 1000 rpm N_{MAX} engines nautical mile fuel consumption percentage differences vs ship speed in summer and winter seasons

As the regard of 900 rpm N_{MAX} MAIN-DE, Fig. 6 shows that the DG-cs plant has a higher engines nautical mile fuel consumption referring the DG-vs one, mainly in winter browsing, with the only exception at 15 knot vessel speed in summer season, speed in which, as already mentioned, there is the passage from two MAIN-DEs running to one. This is due to the greater engine power, to the same ship speed, required by the DG-vs plant.

Fig. 6 put in evidence that the 1000 rpm N_{MAX} engine employed in the DG-vs plant allows an even greater advantage, versus the same engine running in the DG-cs one, in terms of lower nautical mile fuel consumption. The 1000 rpm N_{MAX} engine advantage, compared to the 900 rpm N_{MAX} one is explainable observing its *sfc* contours trend on the engine operating diagram of Figs. 4b and 5b, that permit to DG-vs system to run the engines always in lower *sfc* conditions, which is not possible to the 900 rpm N_{MAX} engines (Figs. 4a and 5a).

Fig. 7 reports the differences between the 900 and 1000 rpm N_{MAX} engines employed in the same diesel-electric propulsion plant type: with DG-cs and with DG-vs. The comparison between the two engines type is carried out, also in this case, to propulsion plants nautical mile fuel consumption (m_f), for different ship speeds in summer and winter seasons.

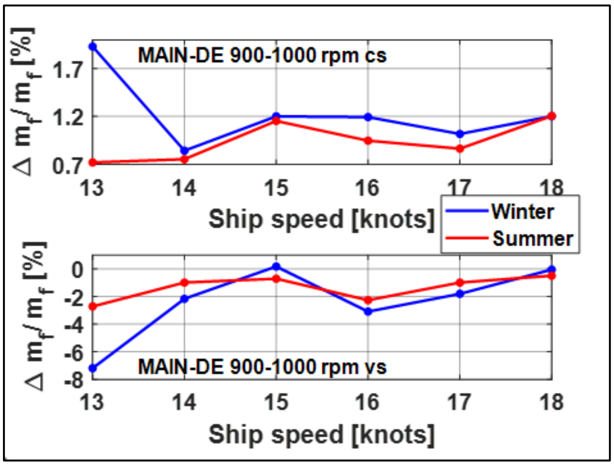


Figure 7 900 and 1000 rpm N_{MAX} engines working in the DG-cs and DG-vs plants nautical mile fuel consumption percentage differences comparison vs ship speed in summer and winter seasons

The data reported in Fig. 7 are determined with:

$$\Delta m_f / m_f \,\% = \frac{m_{f\ 1000\,\mathrm{rpm}\ N\max} - m_{f\ 900\,\mathrm{rpm}\ N\max}}{m_{f\ 900\,\mathrm{rpm}\ N\max}} 100\ [\%] \quad \text{.........} \ (2)$$

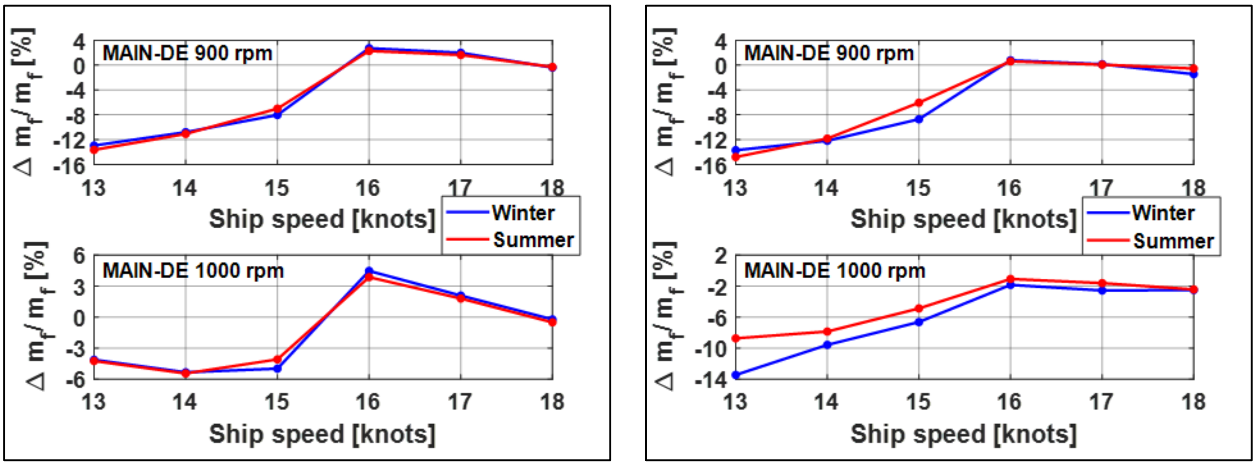
where: $m_{f\ 900\,\mathrm{rpm}\ N\max}$ and $m_{f\ 1000\,\mathrm{rpm}\ N\max}$ are the vessel nautical mile fuel consumption of 900 rpm N_{MAX} and 1000 rpm N_{MAX} engines respectively.

Fig. 7 data, referred the DG-cs plants, show that the 1000 rpm N_{MAX} engine is characterized by a higher nautical mile fuel consumption referring the 900 rpm N_{MAX} one.

On the contrary Fig. 7 shows that, in the DG-vs systems, the 1000 rpm N_{MAX} engine allows a save fuel during navigation, compared to 900 rpm N_{MAX} one. Only at 18 and 15 knots ship speeds, in the winter season, the fuel consumptions of the two engine types is the same.

3.2. Diesel-electric and mechanical propulsion plants comparison

Fig. 8a and 8b reports the percentage difference between the DG-cs and DG-vs diesel-electric systems respectively versus the mechanical propulsion plants, pertinent the ship nautical mile fuel consumption. Both figures are referred to 900 rpm N_{MAX} engines and 1000 rpm N_{MAX} one, for different ship speeds in summer and winter seasons.



a b

Figure 8 DG-cs (a) and DG-vs (b) plants versus mechanical propulsion one nautical mile fuel consumption percentage differences for 900 rpm N_{MAX} and 1000 rpm N_{MAX} engines vs ship speed in summer and winter seasons

The data presented in Fig. 8 are determined by:

$$\Delta m_f / m_f \% = \frac{m_{f\,DE} - m_{f\,MECH}}{m_{f\,MECH}} 100 \; [\%] \text{.......} (3)$$

with: $m_{f\,DE}$ e $m_{f\,MECH}$ are the diesel-electric and mechanical systems nautical mile fuel consumption percentage respectively, referred to the same engine type (900 rpm N_{MAX} and 1000 rpm N_{MAX})

Fig. 8a, referred to 900 rpm N_{MAX} engines, show that for 18 knots ship speed the mechanical plant MAIN-DEs vessel nautical mile fuel consumption is equal to that of the diesel-electric DG-cs one, and little better at 16 and 17 knots. Starting to 15 knots and less vessel speeds the DG-cs nautical mile fuel consumption for all the considered ship speeds becomes progressively smaller and smaller than that of the mechanical plant. Similar considerations can be made as regard to the 1000 rpm N_{MAX} engine (see Fig. 8a), with a greater advantage of the mechanical system at vessel speeds of 15 and 16 knots, and a lesser disadvantage at speeds above 15 knots and lower.

The data reported in Fig. 8b, pertinent the vessel nautical mile fuel consumption comparison between the DG-vs and mechanical plants with 900 rpm N_{MAX} engines, shows a near equity to this parameter at high ship speeds (16-18 knots), and an ever less DG-vs plant nautical mile fuel consumption versus the mechanical one to vessel speed reduction from 15 knots. As the regard of 1000 rpm N_{MAX} engine, Fig. 8b shows that the DG-vs system nautical mile fuel consumption is always lower than that of the mechanical system, with a difference between the two systems which decreases as the ship's speed increases.

The seasonal influence is greater in the plant with DG-vs versus the mechanical one with 1000 rpm N_{MAX} engines (Fig. 8b), especially at lower ship speeds; while the seasonal influence is less felt in all other cases considered in Fig. 8.

4. Propulsion plants economic comparison

For the economic comparison between the different examined ship propulsion plants, two cruises were considered: the first, named 'Pacific cruise', the currently carried out by the vessel [22], the second, named 'Western Mediterranean cruise' is taken from the MSC shipping company website [23].

4.1. Pacific cruise

This cruise, with departure and arrival in Seattle, makes a stop at the following main localities: Seattle, Ketchikan, Juneau, Skagway, Endicott, Seattle, for a total length of 2084 nm. To the cruise timing program [22] the ship speeds between each landfall location were deduced, the average ship speed of each complete cruise was 14.14 knots, 40 annual cruises are considered. From [24] it can observe that the average annual ambient temperature is approximately 13 ° Celsius, typical of the winter climate [25]. Tab. 3, referred to a single cruise, reports for each propulsion plant the vessel

Table 3 Pacific cruise ship propulsion plants total and nautical mile fuel consumptions, fuel saving percentage referring mechanical plant employing 900 rpm N_{MAX} engine

Prop. plant type	Total fuel cons. [t]	Fuel cons./nm [kg/nm]	Fuel saving [%]
Mec. 900 rpm $N_{MAX\,E}$	49.24	23.63	0.00
Mec. 1000 rpm $N_{MAX\,E}$	46.91	22.51	-4.73
DG-cs 900 rpm $N_{MAX\,E}$	44.04	21.13	-10.56
DG-cs 1000 rpm $N_{MAX\,E}$	44.43	21.32	-9.77
DG-vs 900 rpm $N_{MAX\,E}$	43.38	20.82	-11.90
DG-vs 1000 rpm $N_{MAX\,E}$	42.54	20.41	-13.61

total and nautical mile fuel consumption, and the fuel saving percentage, this last determine by:

$$\Delta m_f / m_f \% = \frac{m_{fb} - m_{fb_{ref}}}{m_{fb_{ref}}} 100 \; [\%] \quad \text{…………}(4)$$

Where: m_{fb} and $m_{fb\,ref}$ are the cruise total fuel mass burned by the considered and reference propulsion plant (mechanical one with 900 rpm N_{MAX} engines) respectively.

In Tab. 3, the total fuel consumption is determined adding the engines consumption of each ship route between two docking ports.

4.2. Western Mediterranean cruise

In this cruise [23] the ship travels a ring route of 1569 nm with a stopover in the following localities: Genoa, Marseilles, Palma de Mallorca, Ibiza, Naples, Livorno, Genoa. The cruise vessel average speed is 16.16 knots. From the cruise timing program, it can consider 13 summer cruises (with an average ambient temperature of 29 °Celsius [25]), and 30 winter ones (15 °Celsius of average one). For this cruise two tables (Tab 4 for summer cruise and Tab 5 for winter one) are used to reports, for a single cruise and for each propulsion plant type, the ship total and nautical mile fuel consumptions, and the fuel saving percentage referring the 900 rpm N_{MAX} engines mechanical propulsion plant, this last calculated with eq. (4).

Table 4 Summer western Mediterranean cruise: ship propulsion plants total and nautical mile fuel consumptions, fuel saving percentage referring mechanical plant with 900 rpm N_{MAX} engine

Prop. plant type	Total fuel cons. [t]	Fuel cons./nm [kg/nm]	Fuel saving [%]
Mec. 900 rpm $N_{MAX\,E}$	56.98	36.32	0.00
Mec. 1000 rpm $N_{MAX\,E}$	56.80	36.20	-0.31
DG-cs 900 rpm $N_{MAX\,E}$	56.85	36.23	-0.23
DG-cs 1000 rpm $N_{MAX\,E}$	57.37	36.56	0.67
DG-vs 900 rpm $N_{MAX\,E}$	56.15	35.79	-1.46
DG-vs 1000 rpm $N_{MAX\,E}$	55.47	35.35	-2.72

Table 5 Winter western Mediterranean cruise: ship propulsion plants total and nautical mile fuel consumptions, fuel saving percentage referring mechanical plant with 900 rpm N_{MAX} engine

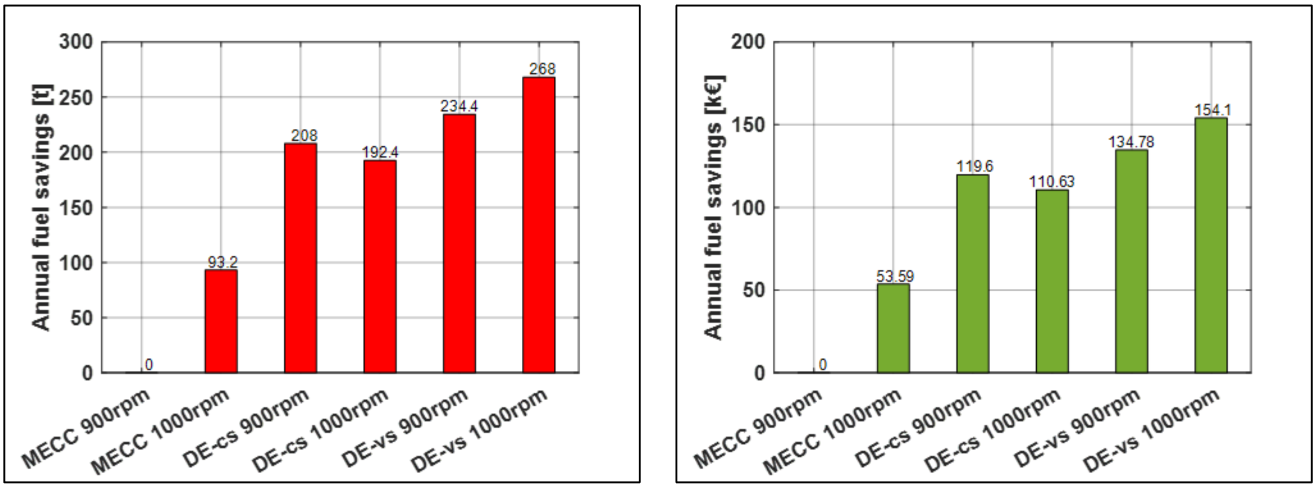
Prop. plant type	**Total fuel cons. [t]**	**Fuel cons./nm [kg/nm]**	**Fuel saving [%]**
Mec. 900 rpm $N_{MAX\,E}$	52.06	33.18	0.00
Mec. 1000 rpm $N_{MAX\,E}$	52.00	33.14	-0.11
DG-cs 900 rpm $N_{MAX\,E}$	52.10	33.21	0.08
DG-cs 1000 rpm $N_{MAX\,E}$	52.67	33.57	1.17
DG-vs 900 rpm $N_{MAX\,E}$	51.22	32.64	-1.61
DG-vs 1000 rpm $N_{MAX\,E}$	50.24	32.02	-3.50

In both tables, the cruise total fuel consumption is calculated with the same logic used for the Pacific cruise analogue parameter determination.

4.3. Cruises comparison

The most important parameter to consider for the two cruises comparison is their average speed, 14.14 for the Pacific cruise and 16.16 for the western Mediterranean one. Also this propulsion plants comparison is referred to the 900 rpm N_{MAX} engines mechanical plant data.

Referring the Pacific cruise, Tab. 3 shows that the greatest fuel saving is obtained from the DG-vs plants, but also the DG-cs ones allow little saving less. This is consistent with the data shown in Fig. 9a, referred to annual tons fuel savings. Also the 1000 rpm N_{MAX} engines mechanical plant obtain a fuel saving of almost 5% compared to 900 rpm N_{MAX} one (Tab. 3). The same considerations are also valid in the comment of Fig. 9b, relating to annual fuel savings, expressed in tons. For the latter, is considered a fuel (MDO) cost of 575 [€/t] [28].



a b

Figure 9 Pacific cruise ship propulsion plants annual fuel saving tons (a) and k€ (b) referring 900 rpm N_{MAX} engines mechanical one

The propulsion plants comparison (always referring the to the 900 rpm N_{MAX} engines mechanical plant), reported in Tab. 4 (for the summer navigation) and Tab. 5 (pertinent the winter one), both pertinent the western Mediterranean cruise, shows that the DG-vs plants (mainly adopting the 1000 rpm N_{MAX} engines) obtain the greatest fuel saving (in summer and winter navigation), but considerably less than that obtained by the same plants in the Pacific cruise, reported in Tab. 3. Tabs. 4 and 5 shows also that the DG-cs plants and the 1000 rpm N_{MAX} engines mechanical one is characterized by fuel savings close to zero, and in some cases negative, especially in summer navigation. These results are consistent with the data reported in Fig. 8, considering the average ship speed (16.16 knots) of this cruise.

The data of the Western Mediterranean cruise, pertinent the annual fuel tons savings (Fig. 10a), confirm the Tabs. 4 and 5 data comments.

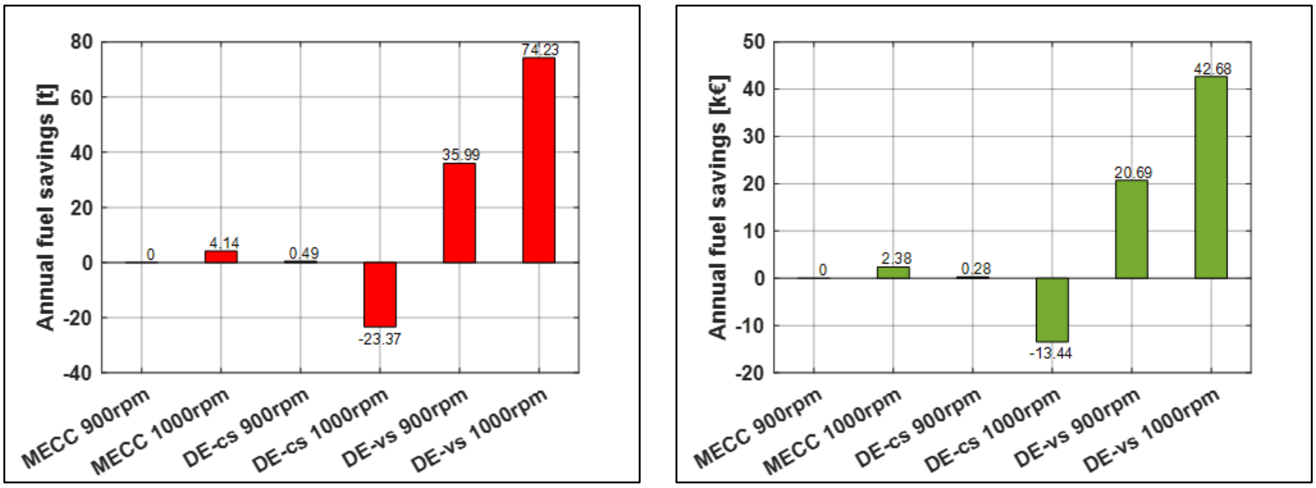


Figure 10 Western Mediterranean cruise ship propulsion plants annual fuel saving tons (a) and k€ (b) referring 900 rpm N_{MAX} engines 'mechanical' one

4.4. Financial evaluations and plants economic comparison

For an economic comparison between the different ship propulsion plants, Tab. 6 reports the considered specific machinery costs, from literature [26,27] and from components manufacturers indications.

Table 6 Propulsion plants specific machinery costs

Machinery item	Specific cost (EUR/kW)
900 rpm N_{MAX} main engine	275
1000 rpm N_{MAX} main engine	264
CPP propulsion line	240
FPP propeller	20
Electric generator	100
Electric motor	100
Electric shaft generator	200
AC/AC electric converter	150
AC/DC or DC/AC electric converter	130

The propulsion systems common components (i.e.: auxiliary diesel-electric generators (DE-EG in Figs. 1 and 2)) are not considered. From Tab. 6 data, each propulsion plants overall machinery cost is determined. The Capital Expenditure (CAPEX) [26], the constant annual instalment:

$$\text{CAPEX} = IC.\,R\frac{(1+R)^n}{(1+R)^n-1} \quad \text{...........(5)}$$

where: *IC* is the initial investment, *n* is the investment lifetime and *R* is the discount rate, 25 years and 10% for *n* and *R* are considered respectively [27].

The annual operational costs are determined by the Operational Expenditure (OPEX) [26], that is the sum of the annual costs, determined by:

$$OPEX = AFC + ALOC + AMC \quad \text{..............} (6)$$

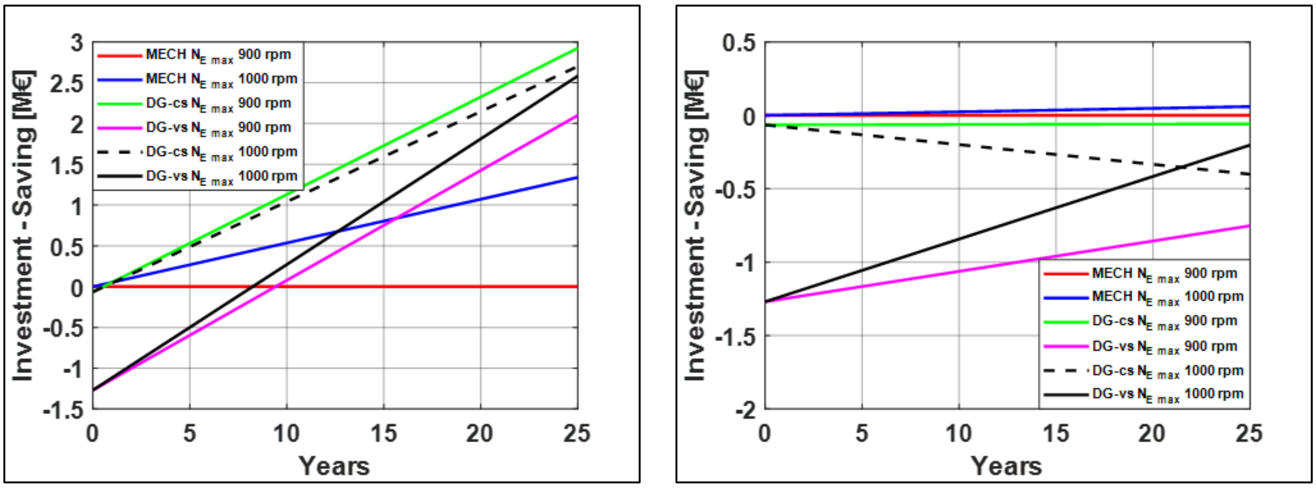
with: AFC the annual fuel cost, ALOC the annual lubricating oil cost, AMC the annual plant maintenance cost. In eq. (6) the terms: ALOC and AMC are considered equals in all the considered plants, as consequence the AFC only is considered to the OPEX calculation for the plants economical comparison.

Considering as CAPEX and OPEX reference value those of the 900 rpm N_{MAX} engines mechanical plants ($CAPEX_{ref\,plant}$ and $OPEX_{ref.\,plant}$ respectively) As shown in Tab. 6, in the mechanical plants the CPP propulsion line and electric shaft generator specific costs about compensate the DG-cs plants electric components one. The DG-vs plants CAPEX is 25% greater to the mechanical reference one, due the greater number of electrical components in these plants, referring the DG-cs one. As also reported, a fuel (Very Low Sulfur Fuel Oil, VLSFO 0.5%) 575 [€/t] constant specific cost [28] is considered.

Tab. 7 shows the normalized $CAPEX/CAPEX_{ref\,plant}$ and the $OPEX\text{-}OPEX_{ref.\,plant}$ annual costs (this last referred to both considered cruises: Pacific and western Mediterranean) differences between the compared propulsion systems.

Table 7 Pacific and Western Mediterranean cruises $CAPEX/CAPEX_{mech}$ percentage and $OPEX\text{-}OPEX_{ref.\,plant}$

Propulsion plant type	**$CAPEX/CAPEX_{ref\,plant}$ [%]**	**$OPEX\text{-}OPEX_{ref..\,plant}$ [M€]**	
		Pacific cruise	**W. Mediterranean cruise**
900 rpm N_{MAX} engines mech. (*ref. plant*)	1	1	1
1000 rpm N_{MAX} engines mechanical	1	0.953	0.998
900 rpm N_{MAX} engines DG-cs	1.03	0.895	1
1000 rpm N_{MAX} engines DG-cs	1.03	0.904	1.010
900 rpm N_{MAX} engines DG-vs	1.25	0.882	0.984
1000 rpm N_{MAX} engines DG-vs	1.25	0.865	0.967



a b

Figure 11 Pacific cruise (a) and Western Mediterranean cruise (b) ship propulsion plants capital investments difference ($CAPEX_{ref\,plant}$ – CAPEX), investment saving and payback time

Fig. 11 shows the vessel propulsion plants initial capital investments difference ($CAPEX_{ref\ plant}$ – CAPEX in year zero of the graph, being the first CAPEX the reference plant, see Tab. 7)), the fuel cost saving referring to 25 years of ship operational life and the payback time. This last is the time in which is recovered, thanks to the sum of the annual costs saving ($OPEX_{ref\ plant}$ – OPEX, in this case the only fuel cost saving), the considered plant machinery eventual higher cost compared to that of the reference plant (900 rpm N_{MAX} engines mechanical one, red line in Fig. 11).

The results reported in Fig. 11a, relating to the Pacific cruise and Fig. 11b, pertinent to Western Mediterranean one are very different from each other.

The comparison between Figs. 11a and 11b, highlights those factors such as: propulsion plant characteristics, cruise average speed, ambient temperature, strongly influence the cruises economic analysis results. It should be noted that variables such as: state of the sea, sea currents, wind speed and direction were not considered in this study.

The data pertinent the Pacific cruise (Fig. 11a) shows that all the considered propulsion plants lead to a saving on the fuel cost at the end of the 25 years, compared to the reference 900 rpm N_{MAX} engines mechanical propulsion plant (red line in the figure).

The most substantial savings are obtained from diesel-electric DG-cs propulsion systems, the figure indeed shows that these plants with DG-cs 900 and 1000 rpm N_{MAX} engines are characterized by very low payback time values, respectively 0.54 and 0.59 years, compared to the DG-vs 900 and 1000 rpm N_{MAX} engines plants, characterized by payback time of 9.42 and 8.24 years respectively.

After 25 years of ship operation the greatest saving on fuel cost is obtained by the plant with DG-cs 900 rpm N_{MAX} engines. The same plant with 1000 rpm N_{MAX} ones obtains only slightly lower results (black dotted line in Fig. 11a). Despite the plants with DG-vs are characterized by greater fuel savings (greater slope of the respective straight lines in Fig. 11a, compared to those of DG-cs plants), the DG-vs plants are penalized by the higher initial investment, compared to DG-cs ones.

Fig. 11a shows that the mechanical plant with 1000 rpm N_{MAX} engines (blue line, allows 1.34 M€ of fuel cost saving, compared to the other mechanical one employing the 900 rpm N_{MAX} engines. This is due to the above mentioned 1000 rpm N_{MAX} engines more favourable power limit curve trend (Fig. 3). Also the fact that in the mechanical propulsion, at lower ship speeds (13-15 kn), the 1000 rpm N_{MAX} engines works with lower specific consumption compared to the reference engine (see Fig. 3), contributes to the aforementioned fuel saving.

As regard to the western Mediterranean cruise, Fig. 11b shows that all diesel-electric plants do not allow a return from the higher initial investment. The plant with DG-cs 900 rpm N_{MAX} engines, has a line indicative of fuel savings (green line in Fig. 11b) practically parallel to the red one of the reference plant. Therefore, in the considered 25 years, it does not recover the slightly greater investment compared to the mechanical reference one. The DG-cs 1000 rpm N_{MAX} engines plant even leads to a continuous loss over time (decreasing slope of the black dotted line in Fig. 11b). In this case there are therefore, in addition to a greater initial investment, compared to the basic mechanical plant, also higher fuel costs, as shows also in Fig. 10.

The DG-vs 900 and 1000 rpm N_{MAX} engines plants, despite both characterized by a fuel saving (mainly the 1000 rpm N_{MAX} one, black continuous line in Fig. 11b), does not allow the greater capital invested total recovery in the considered 25 years.

In the western Mediterranean cruise, among the analysed plants, the most convenient is the mechanical plant with 1000 rpm N_{MAX} engines, which starting to the same initial investment of the reference plant allows, in 25 years, a very modest fuel cost saving (blue line in Fig. 11b).

5. Propulsion plants environmental comparison

As further comparison between the mechanical and diesel-electric propulsion plants, the Energy Efficiency Design Index (EEDI) value is determined as reported in [2-5]. This index is developed by the IMO to quantify the new ships carbon dioxide emissions. The EEDI index conceptual meaning is:

$$\mathrm{EEDI} = \frac{\mathrm{CO_2}\ emissions}{transportwork}\left[\mathrm{g_{CO2}/t/nm}\right] \quad \ldots\ldots\ldots\ldots (7)$$

The procedure for calculating the vessel attained EEDI, for the different propulsion systems here compared, is reported in [5]; this procedure leads to an attained EEDI different value of each of the propulsion systems here considered. In equation (7) the of the 'CO_2 *emissions*' value is proportional to the fuel type and its nautical mile consumption. The ship attained EEDI value must be less than its required one ($EEDI_{req}$), determined with [5]:

$$EEDI_{req} = \left(1 - \frac{X}{100}\right)^{-0.214} EEDI_{ref} \quad \text{.............. (8)}$$

where: X is the time depending percentage value determined as reported in [5]; $EEDI_{ref}$ is the reference EEDI, calculated as reported in [5], for the 'cruise passenger ship having non-conventional propulsion' by:

$$EEDI_{ref} = 170.84\,(GT)^{-0.214} \quad \text{.........(9)}$$

Where GT is the ship gross tonnage (reported in Tab. 1).

For the here considered cruise ship their $EEDI_{req}$ values, referring to the different phases reported in [5], are shown in Fig. 12. In the same figure are reported all the here considered propulsion plants

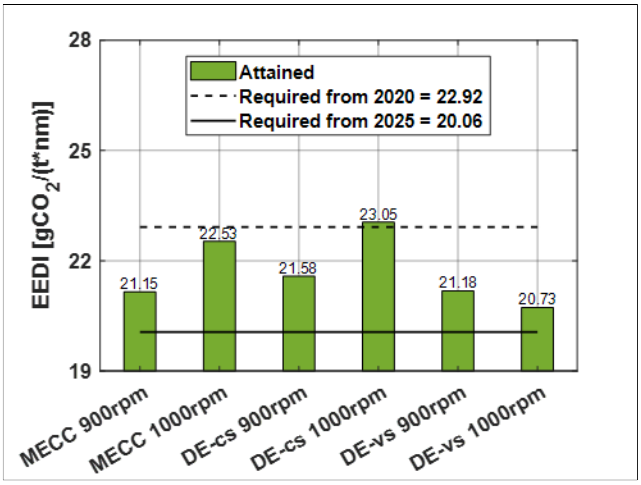


Figure 12 Ship propulsion plants attained EEDI index and required one comparison attained EEDI values

Fig. 12 reports that the DG-cs 1000 rpm N_{MAX} engines plant is the only that exceed the EEDI required by 2020. The attained EEDI of all the other tested propulsion plant options satisfy this $EEDI_{req}$ value limit, but the 1000 rpm N_{MAX} engines mechanical plant satisfy this limit with a little margin. Mechanical and diesel-electric propulsion plants using the 900 rpm N_{MAX} engines have similar attained EEDI values. The DG-vs 1000 rpm N_{MAX} engines plant is characterized by the lowest attained EEDI value, even if slightly better (less) than that of the 900 rpm N_{MAX} engines mechanical plant.

Fig. 12 shows that the diesel-electric systems attained EEDI values are not overall better than those of mechanical ones, this because the procedure to determine this parameter requires that propulsion and diesel generators engines operate at 75 % of the respective MCR value; this implies a vessel speed a little higher than 17 knots for all considered plants, Fig. 8 shows that at this vessel speed the fuel consumption per nautical mile differences between the different propulsion systems are small, while the same figure shows that the diesel-electric systems have lower consumption, compared to the mechanical ones, for ship speeds equal or less than 15 knots.

Fig. 12 reports that the attained EEDI value of all plants exceeds the 2025 required EEDI one.

In 2021 IMO introduce the Operational Carbon Intensity Indicators (CII), that reports the CO2 specific emissions during ship annual operation. Definition for the attained CII index is [7]:

$$\mathrm{CII} = \frac{\sum_{1=1}^{nE} M_{f,i} C_{F,1}}{Capacity \cdot L_a} \quad \text{............ (10)}$$

where: *nE* indicates the number of turned-on prime movers; *Mf* the burned fuel mass; *Cf* the CO2 emission factor; *Capacity* the vessel gross tonnage (GT) and L_a the annually covered nautical miles.

Results from Eq. (10) must be compared with the requested CII_{req} defined as:

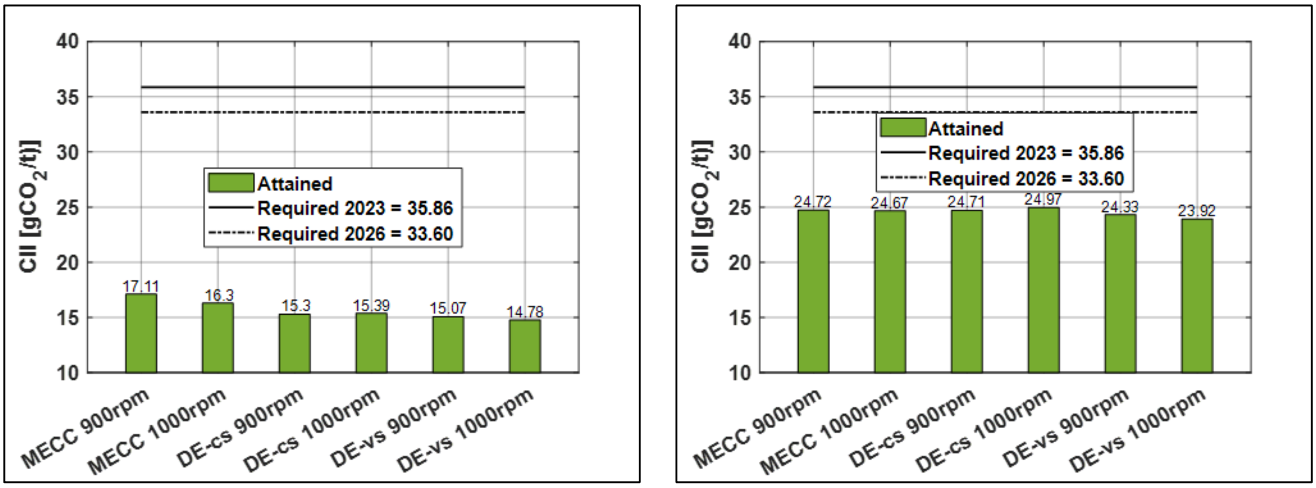
$$\mathrm{CII}_{req} = (1 - Z/100)\mathrm{CII}_{ref} \quad \text{............ (11)}$$

where: *Z* is a reduction factor related to 2019 emissions and provided by IMO up to 2026; CII_{ref} represents a reference value depending by ship size and type as eq. (11).

$$\mathrm{CII}_{ref} = a\,\mathrm{GT}^{c} \quad \text{............ (12)}$$

with: *a* and *c* constants depending to ship type [29].

In eq. (11) IMO imposes *Z* = 5% in 2023 and a 2% reduction is annually added for the successive years up to 2026.



a　　　　　　　　b

Figure 13 Pacific cruise (a) and Western Mediterranean cruise (b) ship propulsion plants attained CII index and required one comparison

Fig. 13 shows the Pacific cruise (a) and Western Mediterranean cruise (b) ship propulsion plants attained CII index and required one comparison. The Western Mediterranean cruise CII is always grater to Pacific cruise one (see Fig. 13), due the higher average speed of this last cruise (16.16 knots) referring the 14.14 knots of the Pacific one. As well known, the greater speed increases the ship fuel consumption. Fig. 13 shows also that in both cruises all the ship propulsion systems satisfy the CCI_{req} limit, including the one expected in 2026, and that both mechanical systems obtain the greater CII values, in the Pacific cruise, while the diesel-electric plant with DG-cs (1000 rpm N_{MAX} engines) has the greater CII value between diesel-electric systems.

Abbreviations

- CPP: controllable pitch propeller
- DE-EG: diesel engine with electric generator
- DG-cs: diesel generator working in constant speed
- DG-vs: diesel generator working in variable speed
- FPP: fixed pitch propeller

- GT: ship gross tonnage
- HEL: ship hotel electric load
- MAIN-DE: propulsion plant main diesel engine
- RR: Rolls-Royce
- SEG: shaft electric generator
- *sfc:* specific fuel consumption

6. Conclusion

In the paper is reported an economic and environmental comparison between mechanical and diesel-electric propulsion plants for a small cruise ship propulsion, a technical comparison between the same propulsion systems has already been carried out in an authors previous article. Both versions of the prime movers Rolls-Royce Bergen marine diesel engine are employed in all plants. This engines type, characterized by a similar rated power, presents very different specific fuel contours trend in the operating diagram. Both diesel-electric plants with diesel generators operating at constant and variable speed have been tested. The propulsion plants comparison is carried out with reference to summer and winter seasons. To systems economic comparison, two different cruises are considered, characterized by a different average ship speed, while the ecological comparison was carried out by determining the ship's EEDI and CII index values, for each propulsion plant considered.

The main considerations drawn from the propulsion plants comparison can be summarized as follows:

- The Pacific cruises (14.14 knots of average speed) economic analysis show the convenience to employ the DG-cs plants. The DG-vs ones, despite their lower annual fuel costs, due their higher plants cost, compared to the DG-cs ones, even after 25 years achieve less economic savings than the latter. The mechanical plant with 1000 rpm N_{MAX} engines is characterized by an interesting economic saving after 25 years, compared to the reference plant (mechanical with 900 rpm N_{MAX} engines), however lower than that achieved with diesel-electric ones. The western Mediterranean cruise (16.16 knots of average speed) economic analysis shows that no any diesel-electric plants has economic advantages compared to the reference mechanical one.
- The EEDI index analysis of the various propulsion plants tested, shows that the mechanical and the diesel-electric plans which use the 900 rpm N_{MAX} engines obtain very similar values of this parameter. On the contrary, the plants with DG-cs and mechanical that use the 1000 rpm N_{MAX} engines are characterized by the higher EEDI values, while the plant with DG-vs equipped with the same engine type, obtain absolute lowest EEDI one.
- The CII index values shows that the value of this parameter is influenced mainly by the cruise average speed, and much less by the ship's propulsion system typology.

The greater efficiency of the diesel-electric propulsion plants, compared to the mechanical ones, detected at lower ship speeds (13-15 knots, including the Pacific cruise, characterized by 14.14 knot of mean ship speed, is due by the fact that in this ship speeds interval only one MAIN-DE is active, which works under high load conditions, and therefore with reduced *sfc* values. In the same ship speeds interval, in the mechanical plants both engines are actives, consequently they operate at reduced power and therefore with high *sfc*. At high ship speeds (16-18 knots), including the western Mediterranean cruise, characterized by 16.16 knots of ship mean speed, in all the analyzed diesel-electric propulsion systems both MAIN-DEs are active, as it happens also in the mechanical plants. To this reason, at high ship speeds, the diesel-electric and mechanical propulsion plants efficiency, and thus the nautical mile fuel consumption and related cost and carbon dioxide emissions, differ little from each other.

In conclusion, from an economic and environmental point of view, the examined diesel-electric propulsion plants are convenient, respect the mechanical ones, in cruises characterized by not high ship speed (i.e.: Pacific cruise), while it is not convenient for travel to ship speeds near to the maximum one (i.e.: western Mediterranean cruise).

Compliance with ethical standards

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Disclosure of conflict of interest

The authors declare no conflict of interest

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