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On the Improvements in Maritime Decarbonization by the Natural Gas-Electric Power System of a Ferry Operating in the Mediterranean Sea

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***Abstract* — the article proposes various methodologies aiming at reducing fuel consumption and emissions of a ro-ro pax ferry currently in service on the Genoa-Palermo route. Maintaining the actual 24-hour service total time (departure, navigation, maneuver, and stopover in the arrival port), a navigation speed reduction is proposed, compensated by the harbor stopover time reduction. The ship's original diesel-mechanical propulsion is replaced (through simulation) by a natural gas-electric system, which also produces on-board electricity, with the possibility of equipping the main thermal engines with specific energy recovery devices. This ensures further fuel consumption and pollutants reduction. In addition to fossil natural gas, biological and synthetic origins are also considered. The outcomes of the proposed solutions are commented from decarbonisation and economical perspectives.**

Keywords—Ship electric power system, natural gas, optimization, CO_2 emissions, alternative fuels, economic analysis

I. INTRODUCTION

The increasingly restrictive international regulations on reducing maritime emissions [1], [2], push the shipping world to consider the use of marine fuels with lower polluting emissions, with particular regard to carbon dioxide [3]. The new fuel types under study are often characterized by a high specific cost [4], therefore in order to reduce fuel costs, it is advisable developing high-efficiency marine propulsion systems. For ships with a large speed profile, such naval ships, shuttle-tankers, ice-breakers, cruise and ferry, the mechanical propulsion plants, where the prime movers are mechanically connected to the propellers, are not the best solution. Nowadays, the above-mentioned vessel types usually employ diesel-electric propulsion systems [5], [6] that allow reducing the active engines number with a better system efficiency to medium and lower ship speed.

In this work, the original mechanical propulsion plant of a Ro-Ro ferry is replaced (by simulation) with a Natural Gas -diesel electric (NG-el) system. The choice of NG as fuel is due to the fact that the Mediterranean sea, where operates the ship chosen as model, will become a SECA (Sulphur Emission Control Area) area from 1 May 2025 [7]. To reduce the ship's carbon footprint, in addition to fossil NG, those of biological and synthetic origin are also considered.To further improve the NG-el system efficiency, the main thermal engines can employ energy recovery devices, such as exhaust gas Waste Heat Recovery (WHR) systems, equipped with Steam Turbine (ST) for the electric energy production [8-11], and/or Hybrid Turbocharger (HTC) [12], [13]. Moreover, aiming at increasing the system efficiency and reducing fuel consumption and emissions, the ship operational profile, operating on the Genoa-Palermo route, was modified, in agreement with the ship's owner.

The article reports a technical, ecological and economic comparison between the NG-el plant with the current operating profile and the same plant equipped with energy recoveries systems (i.e. WHR and HTC) and adopting the new operational profile, by using several NG fuels (fossil, biological, and synthetic origin).

II. ELECTRIC PROPULSION SYSTEM

Figure 1 shows the NG-el power system scheme, designed for ship propulsion and on-board Hotel Electric Load (HEL).

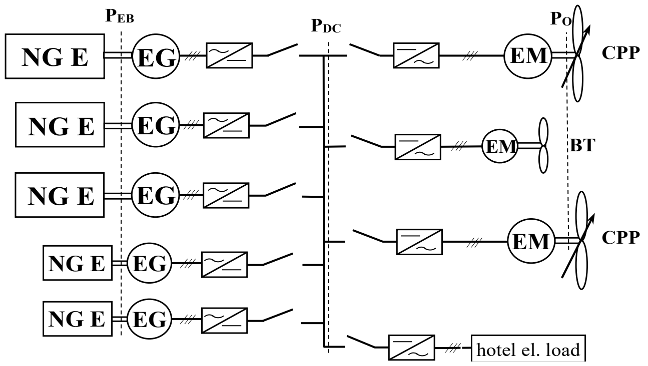

Fig. 1. Developed NG-el system layout

The plant consists of three main Dual Fuel (DF) engines (NGE) and two NG ones, where each engine drives an Electric Generators (EG). All thermal engines work at variable speed, operating at lower specific fuel consumption also at partial loads [14]. The Alternate Current (AC) power is converted into Direct one (P_{DC} in Figure 1) via AC/DC converters. The P_{DC} is then converted into AC one, by DC/AC converters to power the Electric Motor (EM) driving the Controllable Pitch Propeller (CPP), the Bow Thruster (BT), and to meet the HEL. The lower power NG engines (NGE) are active also in port, satisfying the HEL power during ship stops. The three DF NGE can be equipped with WHR and HTC systems (not visualized in Figure 1), improving NG-el plant efficiency.

III. CASE STUDY

An existing Ro-Ro ferry with mechanical propulsion plant is chosen as a case study. This vessel, whose main data are reported in Table I, is equipped with four 4-stroke diesel engines driving 2 CPPs. In this techno-economic analysis, the current diesel-mechanical propulsion has been replaced with the NG-el system of Figure 1, modelled by MATLAB-SIMULINK© software. The adopted thermal engines are three DF MAN 51/60 4-stroke engines (NG E in Figure 1, where two engines deliver a maximum continuous power of 12 MW@514 rpm while the other one delivers 14 MW@514

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rpm) [15], and two Bergen NG 4-stroke engines (2.43 MW@1000 rpm) [16].

TABLE I – EXISTING SHIP MAIN DATA

Main data	Value
Length between perpendiculars, breadth, draft (m)	211/30.4/7.45
Δ, GT, DWT, (t)	26376/49257/9720
Ship maximum continuos speed, v (knots)	28
Number of Passengers/cars	2920/984
Propulsion power (MW) four 4 stroke Wartsila 16V46C (514 rpm)	4 x 16.8
Electric power (MW)/ four Diesel generator engines	4 x 2.43
Propeller number, diameter (m)	2/5.7
HEL power (MW): Summer/ Winter/manoeuvre/port	4.3/3.4/4.65/2.89
Ship thermal load sat. steam (t/h) Summer/Winter/port	3.0/3.5/2.5

IV. NG-ELECTRIC SYSTEM PERFORMANCE OPTIMIZATION

In order to improve the NG-el system performance, both thermal engines power rate and overall NG-el system management are optimized. Therefore, a variable speed control system was adopted to improve the engine efficiency at part load working conditions; in addition, DF engines can use WHR steam plants and/or HTC. The WHR steam plant performance is optimized according to the design procedure described in [10]. Figure 2 shows the DF engine efficiency improvement vs engine speed, thanks to the WHR and HTC systems (only in DF engines). This improvement further increases when both systems are used simultaneously. The NG-el system efficiency (η_E) is determined by:

$$\eta_E = \left(\sum_j P_{EB} + P_{el\,ST} + P_{el\,HTC} + \Phi_{sTL}\right) / \left(\sum_j M_f\, LHV_f\right) \qquad (1)$$

where: j is the thermal engines actives number; P_{EB} the engine brake power; $P_{el\ ST}$ the WHR plant steam turbine electric power; $P_{el\,HTC}$ the HTC electric power; Φ_{sTL} the ship steam thermal load; M_f and LHV_f the fuel mass flow rate and lower heating value, respectively.

The optimization of the NG-el system efficiency requires the determination of the total power demand for vessel propulsion and on-board electrical loads (P_{EB} in Figure 1 that eventually include the electric power produced by WHR steam turbine and HTC, if adopted). Starting from the propeller open water power (P_o), depending on ship speed and HEL, the P_{EB} can be determined by:

$$P_{EB} = \left(\frac{P_0}{\eta_R\, \eta_{EM}\, \eta_{DC/AC}} + \frac{P_H}{\eta_{DC/AC}} - A\right) / \left(\eta_{AC/DC} \cdot \eta_{EG}\right) \qquad (2)$$

where: P_H is the hotel electric power; A is the difference between $P_{el\ WHR\ ST}$ (the WHR plant steam turbine electric power) and $P_{el\,HTC}$ (the HTC system electric power); η_R the propellers rotative efficiency; η_{EM} the propellers electric motor efficiency; $\eta_{DC/AC}$ and $\eta_{AC/DC}$ the direct to alternate current (and vice versa) converters efficiency; η_{EG} the electric generators efficiency. Table II reports the efficiency values adopted for these components [17].

The NG-el systems at medium and lower ship speed permits reducing the active engines number, making the active engine work at the best efficiency conditions, for a better system efficiency. Due to the presence of thermal engines with different power and efficiency values (some of them possibly combined with WHR and HTC systems), the need to develop a procedure that maximizes the efficiency of the active engines in all navigation conditions (ship speed and season) arose.

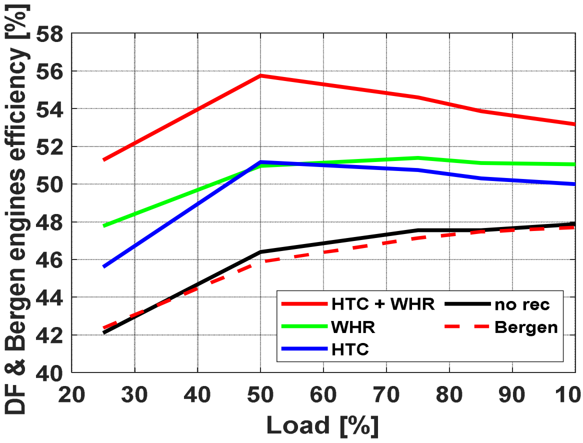

Fig. 2. Bergen and MAN DF engines efficiency vs engine load, adopting the WHR and/or HTC systems

TABLE II – NG-EL SYSTEM COMPONENTS EFFICIENCY VALUES

NG-EL system component efficiency	Values
Propeller rotative efficiency (%)	103.4
Electric motor/generator (%)	96.0/96.5
AD/DC / DC/AC converter (%)	99.0

The MATLAB function *fmincom* was used, for the optimization of the NG-el system efficiency. The optimized variable is the complementary of the overall efficiency of the NG-el system thermal engines (η_{gE}), defined by:

$$1-\eta_{gE} = 1-\left(\sum_j P_{EBj} / \left(\sum_j M_f \cdot LHV_f\right)\right) \qquad (3)$$

with: j the active engines number; P_{EBj} the brake power of the j^{th} engine.

The considered constrains are:

- For each engine, the delivered power is considered between 25% and 90% of the Maximum Continuous Rating (MCR);
- The overall mechanical power required does not exceed 90% of MCR power of all engines.

The *fmincom* input data are:

- Ship speed (knots);
- Navigation season (winter or summer);
- Eventually energy recovery systems: WHR and/or HTC.

Fmincom contains data relating the brake power (P_{EB}), required to the thermal engines as ship speed and navigation season (Figure 3), engines fuel consumption depending on the delivered power, and, electrical energy produced by the DF engines waste energy recovering systems (WHR and HTC, if adopted).

The latter reduces the P_{EB} brake power required by all the thermal engines (considering the efficiency of the AC/DC converters and EM, see eq. 2).

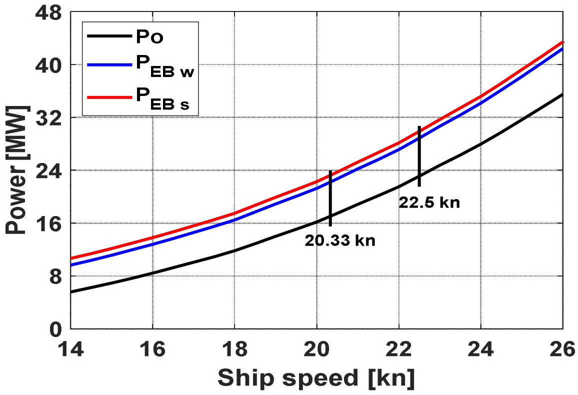

Fig. 3. Ship propellers power and NG-el system engines brake power in winter (W) and summer (S) navigation vs Propeller Bergen and MAN DF engines cogeneration efficiency vs vessel speed

Starting from the input data, *fmincom* determines the number of the working engines and their delivered power that satisfies the vessel mechanical power demand (P_{EB}) with the lowest fuel consumption.

V. ROUTE MANAGEMENT IMPROVEMENT

Currently, the Genoa-Palermo route (or vice versa), 427 nm, is structured as follows: departure, navigation, manoeuvres in the arrival port, stop in the harbour with cargo unloading and loading for a new travel; the duration of all these phases is 24 hours. The vessel navigation speed is 22.5 knots (19 hours of navigation time), the manoeuvre medium speed is 3 knots (1 hour for departure and arrival manoeuvre), and 4 hours stop in port. The authors propose navigation ship speed reduction (20.33 knots), with the ship-owner approval, which entails a navigation time increase from 19 to 21 hours, compensated by a port stopover time reduction from 4 to 2 hours, to keep the total service time in 24 hours (see Table III). This solution reduces the NG-el system engines power (see Figure 3), and consequently the fuel consumption and carbon dioxide emissions. The outcomes shown in Table III refers to both current and new route management. These results focus on: NG-el system active engines (*AE*), engines MCR load and efficiency percentages, overall NG-el system engines efficiency (η_{gE}: eq. 3) and overall NG-el efficiency (η_g). This last efficiency is defined as follows:

$$\eta_g = (2 \cdot P_0 + P_H)/(\textstyle\sum_j M_f \cdot LHV_f) \qquad (4)$$

In Table III, the data regarding the vessel navigation without engine energy recovery systems, with WHR steam plant or HTC and the two systems simultaneous used, are shown respectively. All data are pertinent to summer (S) and winter (W) navigation (ambient temperature greater or lower-equal to 25°C respectively), and to port manoeuvre and stop. For the two latter cases, no energy recovery devices are used. Table III data shows that overall NG-el system efficiency optimizer maintains η_{gE} and η_g values about constant in both actual and new proposed route management, despite the significant NG_el system required power difference (Figure 3). Moreover, both efficiency values increase to the WHR or HTC systems adoption, particularly if both systems are employed at the same time. The outcomes of Table III disclose also that WHR and HTC systems provide very similar results (see also Figure 2), and that η_{gE} and η_g difference is near 4% in navigation conditions, and about 2% in port maneuver and stop, (always in favor of η_{gE}).

TABLE III – CURRENT AND NEW GENOA-PALERMO ROUTE MANAGEMENT: ACTIVE ENGINES (AE), ENGINES LOAD AND EFFICIENCY, NG-EL SYSTEM MECHANICAL AND OVERALL EFFICIENCY, WITHOUT ENERGY RECOVERY, WITH WHR, WITH HTC, WITH WHR+HTC, IN SUMMER (S) AND WINTER (W) NAVIGATION, PORT MAOEUVRE AND PORT STOP

Sizes	**Current**	**New proposal**
Navigation speed (knots)/time (hours)	22.5/19	20.33/21
Harbor manoeuvre (knots)/time (hours)	3/1	3/1
Harbor stop time (hours)	4	2
NG-el system, no recovery, navigation		
S-AE: DF14MW/Load(%MCR)/efficiency(%) W-AE:DF14MW/Load(%MCR)/efficiency(%)	1/77.9/47.6 1/75.6/47.6	1/89.9/47.7 1/85.7/47.6
S-AE: DF12MW/Load(%MCR)/efficiency(%) W-AE:DF12MW/Load(%MCR)/efficiency(%)	2/79.6/47.6 2/76.7/47.6	1/89.9/47.6 1/86.3/47.6
S-AE: Bergen/Load(%MCR)/efficiency(%) W-AE: Bergen/Load(%MCR)/efficiency(%)	0/0/0 0/0/0	0/0/0 0/0/0
S-NG-el system efficency (%)- Mech/Overall W-NG-el system efficency (%)- Mech/Overall	47.4/43.5 47.3/43.4	47.4/43.6 47.3/43.5
NG-el system, with WHR, navigation		
S-AE: DF14MW/Load(%MCR)/efficiency(%) W-AE:DF14MW/Load(%MCR)/efficiency(%)	1/69.6/51.3 1/62.7/51.2	1/78.1/51.3 1/75.8/51.4
S-AE:DF12MW/Load(%MCR)/efficiency(%) W-AE:DF12MW/Load(%MCR)/efficiency(%)	2/75.0/51.4 2/75.0/51.5	1/90.0/51.1 1/85.4/51.1
S-AE: Bergen/Load(%MCR)/efficiency(%) W-AE: Bergen/Load(%MCR)/efficiency(%)	0/0/0 0/0/0	0/0/0 0/0/0
S-NG-el system efficency (%)- Mech/Overall ystem efficency (%)- Mech/Overall	51.2/47.0 51.1/46.9	50.9/46.9 50.9/46.8
NG-el system, with HTC, navigation		
S-AE: DF14MW/Load(%MCR)/efficiency(%) W-AE:DF14MW/Load(%MCR)/efficiency(%)	1/72.3/50.8 1/69.4/50.8	1/53.0/51.1 1/52.9/51.1
S-AE: DF12MW/Load(%MCR)/efficiency(%) W-AE:DF12MW/Load(%MCR)/efficiency(%)	2/74.9/50.8 2/72.4/50.8	2/58.3/51.0 2/54.2/51.1
S-AE: Bergen/Load(%MCR)/efficiency(%) W-AE: Bergen/Load(%MCR)/efficiency(%)	0/0/0 0/0/0	0/0/0 0/0/0
S-NG-el system efficency (%)- Mech/Overall W-NG-el system efficency (%)- Mech/Overall	50.6/46.5 50.5/46.4	50.8/46.7 50.8/46.7
NG-el system, with WHR and HTC, navigation		
S-AE: DF14MW/Load(%MCR)/efficiency(%) W-AE:DF14MW/Load(%MCR)/efficiency(%)	1/56.4/55.5 1/50.0/55.7	1/50.0/55.7 1/47.2/55.2
S-AE: DF12MW/Load(%MCR)/efficiency(%) W-AE:DF12MW/Load(%MCR)/efficiency(%)	2/75.0/54.6 2/74.7/54.6	2/52.1/55.6 2/50.0/55.7
S-AE: Bergen/Load(%MCR)/efficiency(%) W-AE: Bergen/Load(%MCR)/efficiency(%)	0/0/0 0/0/0	0/0/0 0/0/0
S-NG-el system efficency (%)- Mech/Overall W-NG-el system efficency (%)- Mech/Overall	54.6/50.2 54.7/50.2	55.3/50.8 55.4/51.0
NG-el system, no recovery, port manoeuvre		
AE: DF12MW/Load(%MCR)/efficiency(%)	1/42.6/44.4	1/42.6/44.4
NG-el system efficency (%)- Mech/Overall	43.7/41.5	43.7/41.5
NG-el system, no recovery, port stop		
AE: Bergen/Load(%MCR)/efficiency(%)	2/65.3/46.7	2/65.3/46.7
NG-el system efficency (%)- Mech/Overall	44.7/42.5	44.7/42.5

VI. ALTERNATIVE FUELS

A further reduction in the engines carbon dioxide emissions, is achieved by using Biological and Synthetic fuels (their cryogenic liquid state is called: LBG and LSM respectively) in addition to NG fossil fuel (LNG in cryogenic liquid state). Table IV reports the fuels carbon factors (C_F) Well to Wake (WTW) [18] and Tank to Wake (TTW); International Maritime Organization (IMO) considers this last for the Energy Efficiency Existing Ship (EEXI) [19] and Carbon Intensity Indicator CII indexes [20] to evaluate the vessel energetic and ecological efficiencies. The prices considered in Table IV are according to [4].

TABLE IV – FUELS CARBON FACTORS AND SPECIFIC PRICES

Fuel type	$C_{F\ WTW}$ (t_{CO2}/t_F)	$C_{F\ TTW}$ (t_{CO2}/t_F)	Specific price (€/t)
Fossil NG	4.527	2.750	(LNG) 658
Biologic NG	0.946	0.897	(LBG) 1987
Syntetic NG	0.897	0.897	(LSM) 3895
Fossil MDO	3.869	3.332	583

VII. EEXI AND CII INDEXS

The attained EEXI ($EEXI_{att}$) index is evaluated by [19]:

$$EEXI_{att} = \frac{\left(f_j \sum P_{ME(i)} \cdot C_F\ SFC_{ME(i)} - \sum P_{B\ REC} \cdot C_F \cdot SFC\right)}{f_c \cdot DWT \cdot V_{ref}} \qquad (5)$$

where: P_{ME} and SFC are the system engines 75% MCR power and its specific fuel consumption; C_F the TTW fuel carbon factor; $P_{B\ REC}$ the brake power recovered by WHR and /or HTC waste heat recovery systems brake power; DWT the ship deadweight; V_{ref} the vessel speed with all engines running at 75% MCR power; f_j and f_c constants are determined as reported in [19] for *RoRo Passenger* ships (f_j= 0.332, f_c = 1.208). The required EEXI ($EEXI_{req}$) is determined, for *RoRo Passenger* ships, by [19]:

$$EEXI_{req} = \left(1 - \frac{5}{100}\right) 902.59 \cdot DWT^{-0.381} \qquad (6)$$

While the attained CII index (CII_{att}) for *RoRo Passenger* ships is calculated as [20]:

$$CII_{att} = \frac{CO_2\ annual\ mass}{GT \cdot D} \qquad (7)$$

where: D is the ship annual distance traveled (nm); GT is the gross tonnage of the vessel. The required CII (C_{IIreq}) is given by:

$$CII_{req} = \left(1 - \frac{z}{100}\right) 7540 \cdot GT^{-0.587} \qquad (8)$$

where: z is the reduction factor relative to 2019, its values are [20]: 5% to 2023, 7% to 2024, 9% to 2025 and 11% to 2026. To meet the EEXI and CII IMO regulations, the *attained* values must be lower than the respective *required* limits.

VIII. ECONOMIC PARAMTERS

The ship's Annual Costs (AK) are estimated in order to make an economic comparison between the NG-el systems configurations, fuel types and route management. For the *OPEX* calculation, only the fuel costs are considered, whose specific prices are shown in Table IV. The AK is defined as [21]:

$$AK = CAPEX + OPEX \qquad (9)$$

CAPEX equation is:

$$CAPEX = IC \cdot R \frac{(1+R)^n}{(1+R)^n - 1} \qquad (10)$$

where: IC is the investment cost (see Table V and Table VI for system component specific costs); R is the discount rate, assumed as 10; n is the investment lifetime (20 years).

TABLE V – NG-EL SYSTEMS COMPONENTS SPECIFIC COSTS

Component	Specific cost (€/Kw)
Internal combustion engines	368-440
LNG tank and equipments	320
WHR/ HTC systems	110/40
Electric motor/generator	80-110
AC/DC and DC/AC converters	88-110
CPP propeller	140

TABLE VI – OVERALL SYSTEMS COST

NG-el system type	System cost (M€)
No energy recovery systems	44.39
HTC	45.91
WHR	50.64
WHR + HTC	52.16

IX. RESULTS

Data reported in Figures 4-7 are determined as the difference between the values of the existing plant and of the analogue system referring to NG-el system fed with LNG, without engines waste energy recovery and 19 hours of navigation time. The considered annual trips are 199 and 126, in winter and summer seasons, respectively. Figure 4 shows that with the current route management (19 navigation hours), WHR and HTC systems allow respectively 6.10% and 6.98% of annual fuel saving, and 13.07% if the energy recovery devices are used simultaneously. Figure 5 reports that the new proposed route (21 navigation hours) allows fuel savings between 14.5% and 14.9%, accounting for the same energy recovery systems. Figure 6 shows CO_2 annual emission reduction due to LNG fuel, considering the new route management, which resembles the same trend observed for the fuel savings in Figure 5. Actually, with LBG and LSM fuels, the CO_2 emission reduction varies between 81.37% and 83.97%: somewhat larger advantages are observed for LSM. Figure 7 shows that the new route management reduces CO_2 emission in port by 50% with LNG, and 90.1% and 90.6% with LBG and LSM respectively. Referring to the EEXI and CII results, Figures 8 and 9 show that the NG-el system, with new route management and with the fossil NG, meet the IMO limits by a wide margin even without energy recovery systems. From an economic point of view, again referring to the new proposed route management, Figure 10 points out that biological and synthetic fuels significantly increase the annual fuel cost, compared to the fossil NG. The adoption of WHR and/or HTC reduces fuel costs by a small amount, despite entailing savings of even more than 10 M€/year. This last consideration is confirmed by Figure 11, where the payback time route analysis, referred to 20 years, is reported. These data are determined for each tested fuel type by subtracting from the system AK value without energy recovery (continuous black line in Figure 11) the AK value considering the engine waste recovery systems. Figure 11 shows that the energy recovery devices, especially if are used together (WHR + HTC), allow significant savings on the fuel cost, compared to fossil one, and it can be noted that savings increase as the fuel specific cost increases.

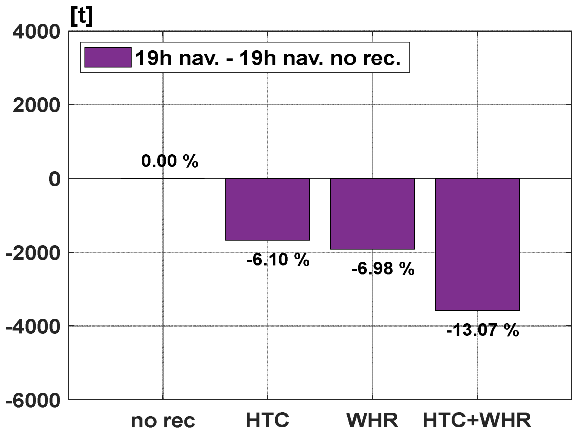

Fig. 4. Difference in LNG annual consumption (19 hours navigation time) compared to NG-el system without engine energy recovery systems

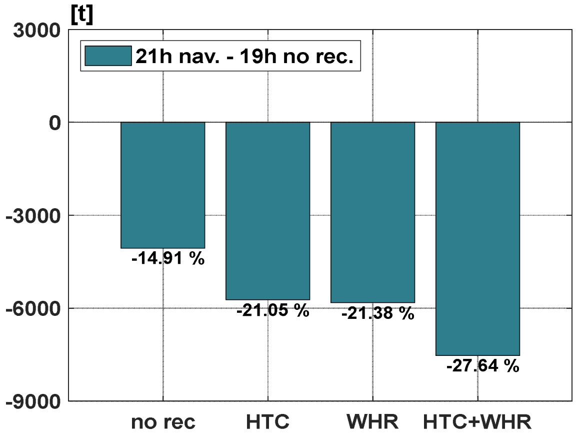

Fig. 5. Difference in LNG fuel annual consumption (21 hours navigation time) in comparison with the NG-el system without engine energy recovery (19 hours navigation time)

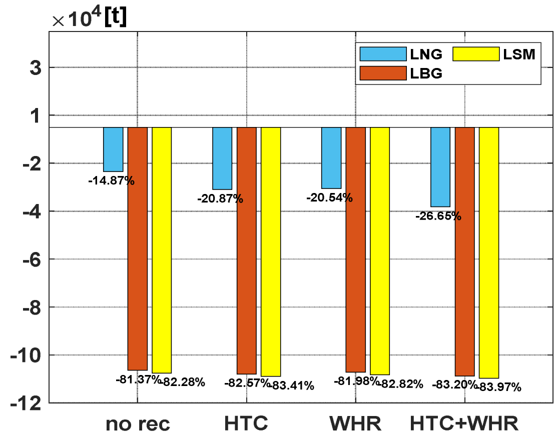

Fig. 6. Difference in CO_2 annual emissions during ship navigation between 21 hours navigation time with LNG, LBG, LSM fuels, compared to LNG fuel (19 hours navigation time) without engine energy recovery systems

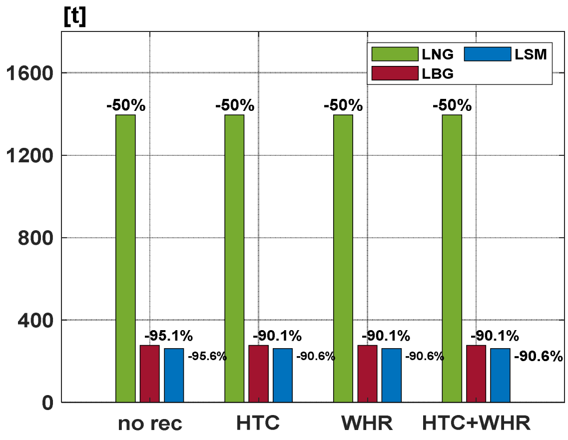

Fig. 7. Difference in CO_2 annual emissions in port between 21 hours ship navigation time with LNG, LBG, LSM fuels, compared to LNG fuel (19 hours navigation time) without engine energy recovery systems

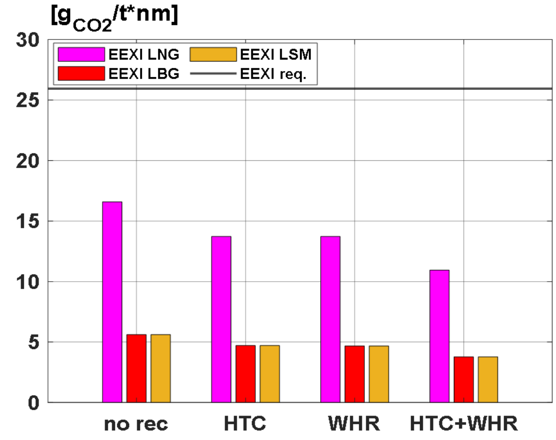

Fig. 8. EEXI values (21 hours ship navigation time) due to LNG, LBG, LSM fuels with and without engine energy recovery systems

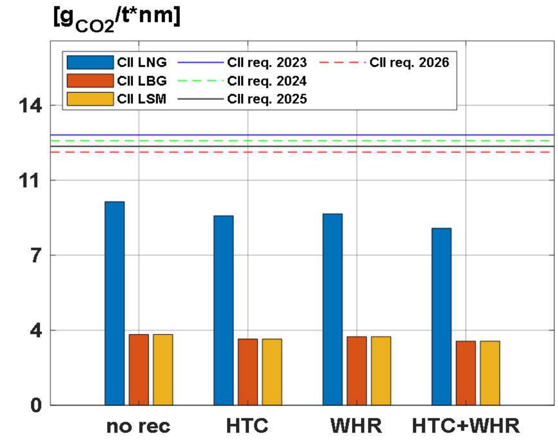

Fig. 9. Ship CII index values (21 hours ship navigation time) due to LNG, LBG, LSM fuel with and without engine energy recovery systems

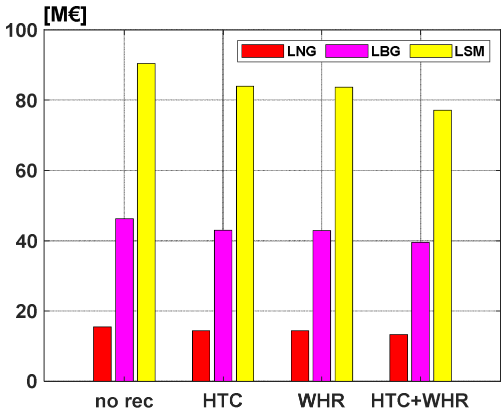

Fig. 10. Ship annual fuel cost (21 hours ship navigation time) due to LNG, LBG, LSM fuels with and without engine energy recovery systems

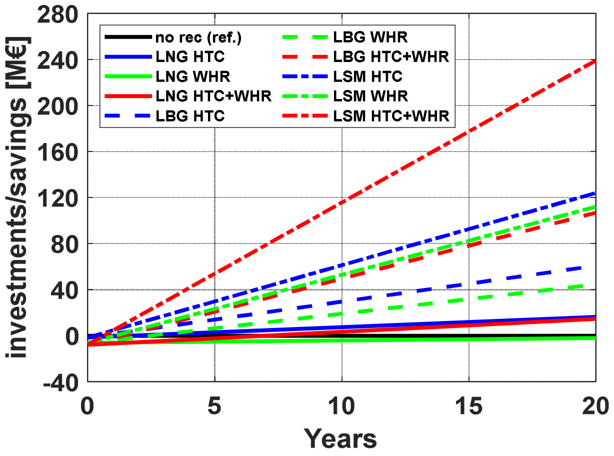

Fig. 11. Economic comparison (21 hours navigation time) with engines fed by LNG, LBG and LSM referring to the case without energy recovery

X. CONCLUSIONS

The main considerations of the present study are:

- the proposed NG-el system, thanks to its performance optimizer, allows a high system efficiency, which remains almost constant, also for very low values of the working engines power;
- the new proposed route management allows a fuel consumption reduction of almost 15%;
- WHR and HTC systems have about the same efficiency;
- the HTC system benefits of less space and cost compared to the WHR, each of them reduces fuel consumption approximately by 6%, double if both are used;
- NG of biological and synthetic origin drastically reduce CO$_2$ emissions, but significantly increase fuel costs, especially when using LSM.

ACKNOWLEDGMENT

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REFERENCES

[1] International Maritime Organization (IMO), “Resolution MEPC.334/76,2021 guidelines on survey and certification on attained energy efficiency existing ship index (EEXI)”, June 17, 2021.

[2] International Maritime Organization (IMO), “Resolution MEPC.336/76, 2021 guidelines on operational carbon intensity indicators and the calculation methods (CCI)”, June 17, 2021.

[3] A. Fan, J. Wang, Y. He, M. Perčić, N. Vladimir, and L. Yang, “Decarbonising inland ship power system: alternative solution and assessment method”, Energy, 226, 2021, 120266.

[4] D. Nelissen, J. Faber, R. Van der Veen, A. Van Grinsven, H. Shanthi, and E. Van den Toorn, “Availability and costs of liquefied bio and synthetic methane”, The maritime shipping perspective, Delft, CE Delft, march 2020, Publication code: 20.190236.031.

[5] IMarE, “Electric propulsion, the effective solution?”, The Institute of Marine Engineers, 1995.

[6] C. Nuchturee, T. Li, and H. Xia, “Energy efficiency of integrated electric propulsion for ships – a review”, Renew. Sustain. Energy Rev., 134, 2020, 110145, pp.1364-0321/©, 2020 Elsevier Ltd.

[7] International Maritime Organization (IMO), “Maritime Environment Protection Committee (MECP), 79TH session”, 12-16 December, 2022.

[8] M. Altosole, M. Laviola, A. Trucco, and A Sabattini, “Waste heat recovery systems from marine diesel engines: comparison between new design and retrofitting solutions”, in Maritime Technology and Engineering - Proceedings of MARTECH 2014, 2015, pp. 735-742.

[9] M. Altosole, U. Campora, S. Donnarumma, and R. Zaccone, “Simulation techniques for design and control of a waste heat recovery system in marine natural gas propulsion applications”, J. Mar. Sci. Eng., vol. 7, issue 11, Article number 397, 2019.

[10] M. Altosole, G. Benvenuto, U. Campora, and R. Zaccone, “Comparison of Saturated and Superheated Steam Plants for Waste-Heat Recovery of Dual-Fuel Marine Engines”, Energies, 2020, vol. 13, Issue 4, Article number 985, DOI:10.3390/en13040985.

[11] M. Altosole, U. Campora, L. Mocerino, and R. Zaccone, “An innovative variable layout steam plant for waste heat recovery from marine dual-fuel engines”, Ships and Offshore Structures, 2023, 18(3), pp. 429–437, DOI:10.1080/17445302.2022.2061769.

[12] M. Altosole, G. Benvenuto, U. Campora, F. Silvestro and G. Terlizzi, “Efficiency improvement of a natural gas marine engine using a hybrid turbocharger”, Energies, 2018, vol. 11, issue 8, article number 1924, August 2018, DOI:10.3390/en11071924.

[13] M. Altosole, F. Balsamo, U. Campora, and L. Mocerino, “Marine dual-fuel engine power smart management by hybrid turbocharging Systems”, J. Mar. Sci. Eng., 2021, vol. 9, Issue 6, n 663, 16 pages, DOI: 10.3390/jmse9060663.

[14] R. Zaccone, U. Campora, and M. Martelli, “Optimization of a hybrid diesel-electric ship propulsion and power generation system using a genetic algorithm”, J. Mar. Sci. Eng., 2021, 9, 587, 14 pages, published June, 2021, eISSN: 2077-1312, pp. 1-14.

[15] MAN, “Four-stroke dual-fuel engine compliant with, IMO Tier II / IMO Tier III, MAN 51/60DF Project Guide – Marine”, 2015.

[16] Rolls-Royce Bergen engine type C, fuel gas operation, Project Guide, 2015.

[17] Ö. Emre Karaçay, and O. Azmi Özsoysal, “Techno-economic investigation of alternative propulsion systems for tugboats”, Energy Convers. Manag., vol. 12, December 2021, 100140, https://doi.org/10.1016/j.ecmx.2021.100140.

[18] D. Nelissen, A. Kleijn, and J. Faber, “FuelEU Maritime and EU ETS Sound incentives for the fuel choice?”, Delft, CE Delft, February, 2022, available from: www.cedelft.eu.

[19] International Maritime Organization (IMO), “Resolution MEPC.333/76, 2021 Guidelines on the method of calculation of the attained energy efficiency existing ship index (EEXI)”, London, June 17, 2021.

[20] International Maritime Organization (IMO), “Resolution MEPC.336/76, 2021 Guidelines on operational carbon intensity indicators and the calculation methods (CII Guidelines, G1)”, June 17, 2021.

[21] A. Dotto, U. Campora, and F. Satta, “Feasibility study of an integrated COGES-DF engine power plant in LNG propulsion for a cruise-ferry”, Energy Convers. Manag., 2021, 245:1