Numerical and Experimental Investigation for the Performance Assessment of Full Electric Marine Propulsion Plant

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ABSTRACT: The advantage of hybrid diesel-electric propulsion is well known in terms of fuel consumption, especially for ships with variegated speed profiles or with different propulsion loads. Nowadays several hybrid configurations are available and in the preliminary design phase, the selection of the best configuration among several options could be a time-consuming task. Therefore, in this paper, a methodology is proposed, based on the main propulsion design parameters, to identify the global ship energy efficiency in function of the operational profile, considering both design and off-design conditions. In order to validate the method, a sea trial campaign has been done and the records have been analyzed. The developed tool helps, during the design phase, to choose the optimal propulsion configuration, number, type, and size, of the main engines and generators. The methodology is used to compare two design solutions, a conventional diesel propulsion and a proposed full electric plant using a 'father and son' power generation.

1 INTRODUCTION

Since a long time, the energy efficiency is one of the most important aspects, together with the safety during navigation, for the ship owners.

Nowadays several strategies could be adopted, to improve the propulsion ship performance in terms of fuel consumption, for example, optimizing from an hydrodynamics point of view (Nelson et al. 2013), both the hull and propeller geometry; this solution is only feasible for a new ship.

Fluoropolymer painting increases the energy efficiency of existing hulls, by providing a low-friction, ultra-smooth surface on which organisms have great difficulty settling (Candries et al. 2000).

Another solution is to replace fixed pitch propellers with controllable pitch propellers (Altosole et al. 2012, 2014) or ducted propellers; this last device is suitable for heavily loaded propellers, such as trawlers and tugboats, where high thrust is needed at low vessel speed (Martelli et al. 2016).

Some solutions recently proposed to increase the thermal efficiency of diesel engines, i.e. magnetic devices for fuel condition, were tested and no improvement was assessed (Gabiña et al. 2016).

In the case of an existing boat, the efficiency could be improved replacing the main propulsion components with more efficient and newer ones, or it is possible to redesign the whole propulsion plant.

The latter solution will be deep analyzed in this paper.

Energy optimization requires engineering studies and real data feedback. Engineering studies require technical data and drawings of existing vessels, generally not available. This drawback can be overcome by the availability of real field data, in particular, to better understand which kind of improvements could be done it is necessary to define the energy profile of the vessel. This kind of data come from the Energy Audit, an engineering test for the monitoring of energy usage during normal fishing activities (Buglioni et al. 2012, Notti & Sala 2014).

To analyze the huge amount of data, and to help the designer to develop a new power architecture is needed rigorous mathematical models and a computer-based tool.

Therefore, in this paper, a methodology is proposed, based on the main propulsion design parameters, to identify the global ship energy efficiency in function of the operational profile, considering both design and off-design conditions.

The developed tool helps, during the design phase, to choose the optimal propulsion configuration, number, type, and size, of the main engines and generators. For validation purposes, the propulsion plant of an existing oceanographic vessel, equipped with a four-stroke diesel engine that drives a ducted controllable pitch propeller is modeled.

To confirm the method reliability a sea trial campaign has been done and the data have been analyzed (Notti & Sala 2012). The proposed methodology was also used to design a new propulsion configuration, with electric prime movers and considering an asymmetrical power generation with a battery pack. This configuration gives a great flexibility to the propulsion plant and it is optimized for all the different missions that oceanographic vessels have to deal with.

At the end of the paper, a comparison between the two design solutions, existing and the new one is carried out; the saving in term of fuel consumption during several real operative situations is highlighted.

2 EFFICIENCY EVALUATION

The global propulsive efficiency is more than the combination of the energy efficiency of the isolated machinery or elements that compose the propulsion plant. All the propulsion elements (engine, gearbox, bearing, propulsor) interact, affecting each other. In this view, a mathematical model, static or dynamic, is needed first to assess the single elements behavior, secondary to catch the mutual interactions. Since in design phase, thousands of combinations should be studied, to obtain reliable results in a reasonable time, a steady state approach has been used. In the following, the methods adopted to model the engine, the propeller, the transmission line and the mutual interaction are presented.

The first element to be modeled is the thermal engines (both prime mover/s and diesel generator/s). A great number of propulsion plants deal with several operation profiles that differ in terms of ship speed, propulsor loads, boundary conditions and constraints. Due to economical (Castles et al. 2009), environmental (Eyring et al. 2005, Larsen et al.2015), and legislative (IMO 2009a, b) constraints, the knowledge of the fuel consumption on the whole set of engine working points is a crucial aspect. Based on previous motivations, the standard data, often available from engine manufacturers, only on a cubic power request, are not enough. The specific fuel consumptions q_s , and consequently the engine efficiency η_{Eng}, is assessed using a polynomial surface, its form is reported in following:

$$q_s\,(N,P_b) = \sum_{i=1}^{4}\sum_{j=1}^{4} P_{ij}\; N^i\; {P_b}^j \qquad (1)$$

Where P_{ij} are the coefficients of the polynomial, obtain through the analysis of several fuel consumption data related to different four stroke diesel engines.

The fuel map obtained is function of both of engine speed N, and of brake power P_B, and used as response surface (Altosole & Figari 2011).

The propeller performances are evaluated using open water characteristics, thanks to which it is possible to evaluate the non-dimensional thrust coefficient K_T and torque coefficient K_Q depending on both the non-dimensional advance coefficient J and the propeller pitch angle φ.

$$\begin{aligned} T &= K_T(J,\varphi)\,\rho\, n^2\, D^4 \\ Q_O &= K_Q(J,\varphi)\,\rho\, n^2\, D^5 \end{aligned} \qquad (2)$$

Where ρ is the seawater density, D is the propeller diameter and n is the propeller revolution regime. Among the several methods that could be used to evaluate the propeller characteristics, the systematic series approach (Kuiper 1992) results more suitable for this application, due to its low computational cost.

The ship drag and the propulsive coefficients can be modeled using three different methods: towing tank tests, statistical regression (Holtrop & Mennen 1982, Von Oortmerssen 1971) or the systematic series.

Once both hull and propeller performance, together with their mutual interaction, are known, it is possible to obtain the equilibrium point in term of shaft line revolution and required power, using the well know engine-propeller matching procedure. The drag-thrust equilibrium problem is solved using the non-dimensional factor, K_T/J^2 , from which the advance coefficient J, the propeller rotational regime n and the required propeller power P_B are obtained, for each velocity and for each propeller pitch.

After this, to evaluate the propulsive energy consumption of the vessels, first, the overall propulsive coefficient (OPC) has to be calculated (17th ITTC 1984) as follows:

$$O.P.C. = \frac{P_E}{P_B} = \frac{1-t}{1-w}\eta_o\eta_r\eta_m \qquad (3)$$

Where P_E is the effective power; P_B is the brake power; η_o is the propeller open water efficiency; η_r is the relative rotative efficiency; and η_m is the mechanical efficiency defined as the product between the gear and bearings efficiencies.

The overall propulsive coefficient it is not sufficient to identify the global ship efficiency because does not take into account the efficiency of the prime mover. In fact, an optimum working point from the hydrodynamic point of view not always matches with a good performing engine working point. In order to define an holistic assessment of the propulsion energy efficiency, the mass fuel flow rate $\dot{m}_f$ has been introduced, depending on specific fuel consumption q_s and the delivered power P_B, see Equation 4. The latter is then used to define the global propulsive energy index η_{TOT} as the ratio between the effective power P_E and the chemical fuel power $\dot{m}_f H_i$, as shown in Equation 5, where H_i is the lower heating value of the fuel. By substitution, it was possible to obtain η_{TOT} (Martelli et al. 2016) as shown in Equation 6.

$$\dot{m}_f = q_s P_B \tag{4}$$

$$\eta_{TOT} = \frac{P_E}{\dot{m}_f H_i} \tag{5}$$

$$\eta_{TOT} = \frac{OPC}{q_s H_i} \tag{6}$$

The ‘propulsion global energy efficiency’ could be now assessed for several speeds, under different operational conditions, and in case that the propulsion plant has two degrees of freedom, for all the possible equilibrium pair (n, φ) as shown in Figure 5.

In order to have a complete overview of the energy production and demand, it will be mandatory to assess also the ‘ship global efficiency’; in authors’ opinion this means to take into account also the energy consumption, or the power required by the auxiliary systems, P_{Aux}.

$$\eta_{Ship} = \frac{P_E + P_{Aux}}{\sum_{j=1}^{n} \dot{m}_{f_j} H_{i_j}} \tag{7}$$

This last formula expresses the efficiency of the whole ship during operations, taking into account the total amount of the fuel burned onboard. Since the lack of experimental data, this aspect will be the target of further analysis in future.

3 CASE STUDY

To validate the proposed methodology, the performance of the Italian National Research Council (CNR) ship "G. Dallaporta" are analyzed. A numerical model has been developed and the performance and energy efficiency has been evaluated.

Analyzing the historical navigation data, an operational profile made up by four different missions and the harbor stops has been identified. The four missions are briefly described in the following.

Table 1. Main characteristics of the R/V "G. Dallaporta".

Year of construction	2001
Length overall (LOA)	35.0 m
Breadth	7.67 m
Draft	3.0 m
Gross tonnage	286 GT
Displacement	312 tons
Main engine	Wärtsilä 810kW
Auxiliary Engine	Cat170 kVA
Propeller	CPP in Nozzle
Crew	7 + 11 researchers

Figure 1. R/V “G. Dallaporta”.

Sea Water Sampling: The ship sails from the harbor to the sea area to be sampled at cruising speed. Once the sampling area is reached, the ship stops at the first sampling point, collects the water and moves to the next point, usually about four miles away. About 20 minutes, sailing at cruising speed, are needed to this transfer phase. The duration of this type of mission is not easily defined because it depends on the number of stations sampled.

Offshore Platform Monitoring: The pattern of this task is similar to the previous one. The difference is that the sampling takes place at four points around the offshore platform, about 1.5 miles far away from it, plus four additional points near the platform along which the ship moves. Such sampling takes about 3 hours and a half, including one and a half hour needed for stations near the platform.

Acoustic Survey: The campaign aims to associate the acoustic survey of the pelagic fishery with the actual amount of biomass sampled by fishing. The ship, in the sampling area, carries out a serpentine pathway to cover a large sea area. This path is carried out at a speed not exceeding nine knots, in order to avoid disturbances to the acoustic equipment. At constant intervals, the ship shoots and tows the fishing gear for about 30 minutes at a speed of 4 knots.

Fishing gear testing: In this activity, the performance and the behaviour of standard and innovative fishing gears, are tested; the ship tows the fishing gear, with a high propeller load, with a speed between three and four knots for about one hour, five times a day, three days a week.

The ship operates overall more than 200 days per years, and the summary of the previously described activities are shown in Table 2.

Table 2. “G. Dallaporta” Operational profile.

	Days per Year	Total Hours	Percentage
	[gg]	[h]	[%]
Platform monitoring & Water Sampling	63	530	31,2%
Acoustic Survey	26	273	12,9%
Fishing gear testing	113	1300	55,9%

The step forward is the calibration of both ship and towing instruments. A comparison of the ship drag obtained with two different methods (Holtrop & Mennen 1982, Von Oortmerssen 1971), and towing tank data are presented in Figure 2. Von Oortemerssen results present a hump not feasible for a displacement hull. This strange behavior was due to some typos in the original paper (Helmore 2008). Due to these uncertainties, all the next evaluations were performed by using the towing tank data, because available.

The propeller performance are modeled using the ducted propeller series published by (Kuiper 1992). The results are shown in Figure 3 as function of the propeller pitch angle.

The application of Equation 1, to assess the fuel consumption in the whole engine envelope, leads to the results shown in Figure 4. In the Figure, the calculated fuel consumption $[l/h]$, is compared with the data coming from the engine manufacturer, available only on the nominal propeller ‘cubic’ curve. The discrepancy between data is less than 4%, in line with the measurements tolerance.

The global propulsive efficiency is calculated for all the operational profiles, for several ship speed and for different propeller pitch angle. For sake of shortness, only the results concerning the navigation condition are shown in Figure 5. This figure suggests also the optimum cruising speed, referred to the propulsion energy index.

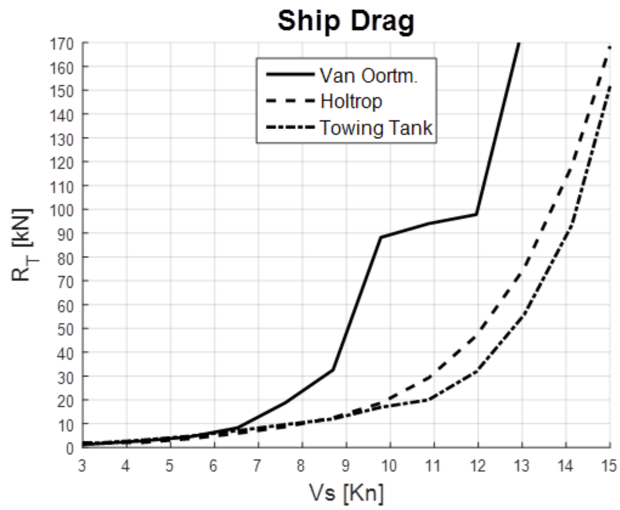

Figure 2. Ship Drag comparison.

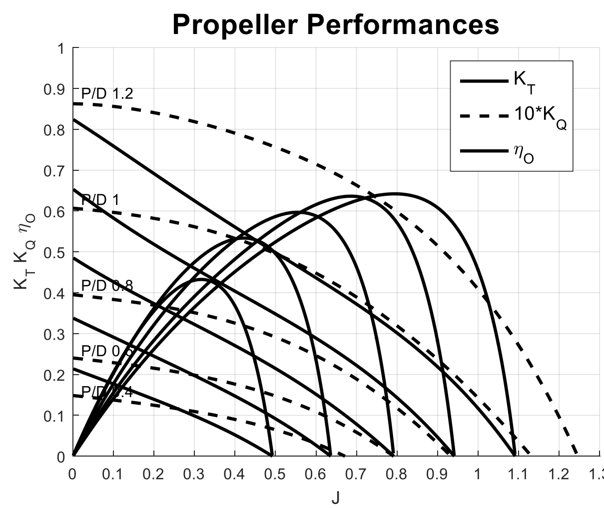

Figure 3. Propeller Open Water Characteristics.

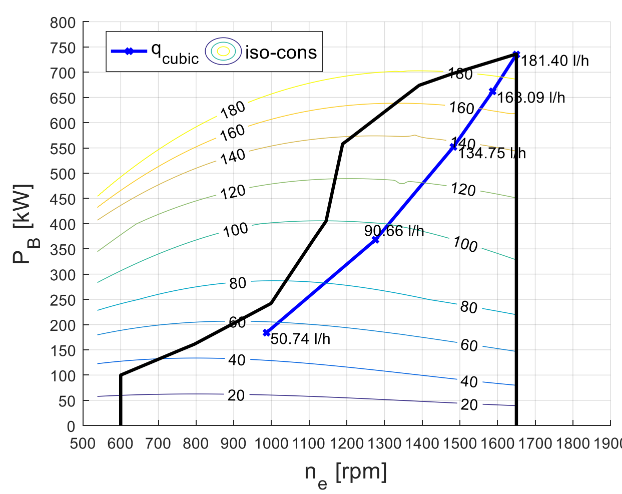

Figure 4. Engine Fuel Consumption map.

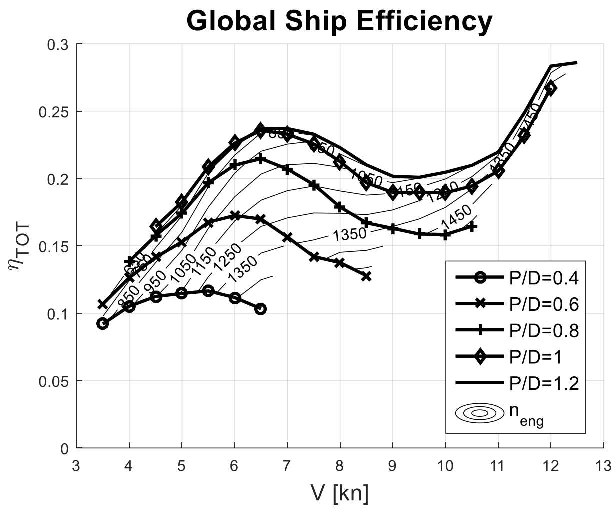

Figure 5. Propulsion Energy Efficiency.

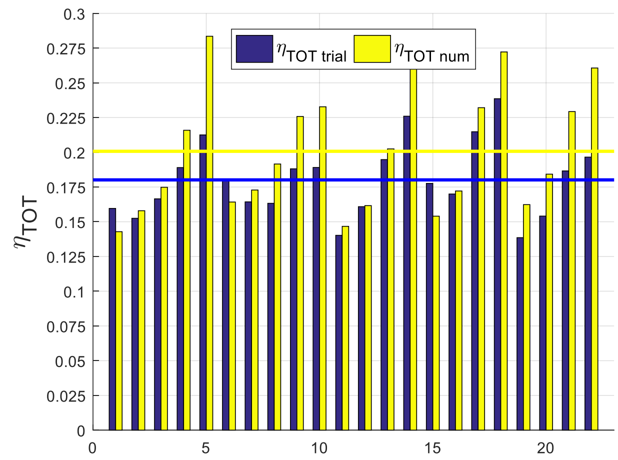

Figure 6. Energy Efficiency: Predicted vs. Measured.

4 SEA TRIALS

Sea trials campaign is fully described in (Capasso et al. 2016). It has been carried out during regular sampling and sailing activities from 2011 to 2015 aiming at the definition of the energy profile of the vessel (Sala et al. 2011, Notti & Sala 2012).

The collected records range from 20 up to 40 hours of continuous monitoring of the propulsion system.

Vessel's position, course, and speed are monitored with a digital GPS. The vessel is also equipped with an log to measure the speed through water.

The propulsion system is equipped with a torque meters, for the assessment of the delivered torque. Two flow meter are installed on the fuel feed line and a on the return line. An optical encoder operated as rotation counter for the calculation of the shaft rotational speed. Each channel has been sampled every two seconds.

Figure 6 shows a comparison of all the propulsive efficiencies corresponding to the 22 different tests done in navigation mode, varying both engine speed and propeller pitch angle.

The results are compared with the results of the sea trials. The average of the global propulsive energy efficiency is about 0.18 for experiments and about 0.2 using the numerical tool. An average difference of 8% between the real and the forecasted values is experienced.

The difference could be due to the meteo-marine conditions (i.e. current), not monitored during the sea trials and object of future work. In the authors' opinion, the results are reliable enough to be used for the design of a new propulsion plant using the proposed methodology.

5 PROPOSED HYBRID ARCHITECTURE

By using the developed numerical code, several feasible plant architecture have been evaluated, and after a preliminary selection, taking into account the structural constrains, the promising solutions is to use an unique electric motor as prime mover. Therefore, the attention will be focused on the power generation. To the correct assessment of the energy production, and of the energy storage capacity, is not sufficient the study only of the ship mission profile, a second step is needed. For this reason, every mission (Acoustic Survey, Water Sampling, Platform Monitoring and Fishing gear testing) is divided into the sub-missions. The sub-missions are defined as the part of the activities where the propulsion power requirement maintains similar magnitude. For an oceanographic vessel, five sub-missions have been identified: Navigation full load, Navigation half load, Towing, Manoeuvring, Water Sampling.

Using the propeller-engine equilibrium procedure, and assessing the optimum propeller pitch, the propulsion power requirement for each task is evaluated, and the results shown in the next figure.

Once known the required power for every condition, it is possible to choose the diesel generators number and size. Due to space constraints, the number of a diesel generator is set to two.

As shown in Figure 7, the best solution is to adopt a *"Father & Son"* configuration. This means that the two diesel generators have different power levels. The use of asymmetric power generation allows the engines to run near their optimum working point, in almost all conditions.

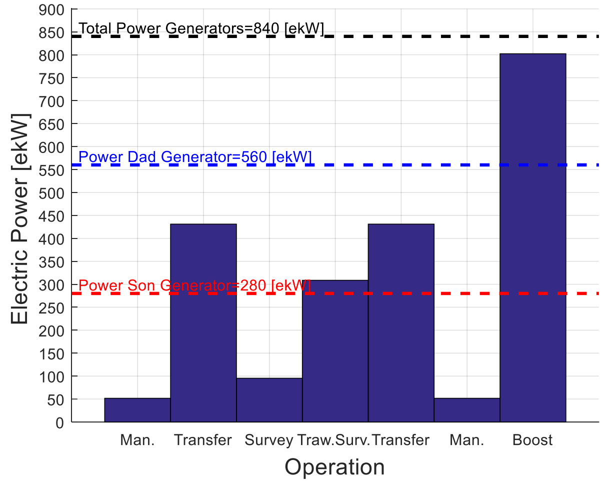

Figure 7. Power request for each task during the acoustic survey.

An additional feature of the proposed full electric propulsion plant is the use of the energy storage in accumulators. This solution leads to navigate in so-called "*ZEM*" mode (zero emission mode) where all the thermal engines are switched off. Several advantages of *ZEM* are present: the silent navigation, avoiding disturbances coming from the noise and vibrations of internal combustion engines; the possibility to navigate in marine protected area; the possibility to increase the overall efficiency recharging the batteries when the engine works at partial load (of course the batteries could be recharged with a shore connection, during harbor stops). Actually, the energy density of batteries does not allow a long range, but when batteries technology becomes mature, this bottleneck could be overtaken.

Therefore, to design the battery pack it is useful to express the total energy spent to perform each subtask, as shown in Figure 8. This figure support the ship designer to choose both the number and the capacity of the batteries. In fact, having in mind which task should be accomplished in "*ZEM*" mode, the correct sizing of the battery pack is possible.

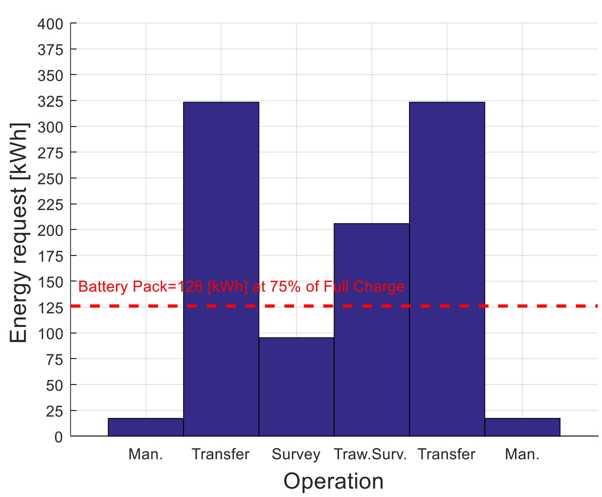

Figure 8. Acoustic Survey: Energy request.

Eventually, after all the previous considerations, the proposed propulsive architecture is shown in Figure 9. With the new propulsive configuration the ship would sail in ten different propulsive configurations, each of which is optimized to perform every single sub-task with a maximum energy efficiency:

- Batteries (ZEM)
- "Son" diesel generator
- "Son" diesel generator + Batteries IN
- "Son" diesel generator + Recharge Batteries
- "Father" diesel generator
- "Father" diesel generator + Batteries IN
- "Father" diesel generator + Recharge Batteries
- "Father" diesel generator +"Son" diesel generator
- "Father" diesel generator +"Son" diesel generator + Batteries IN
- "Father" diesel generator +"Son" diesel generator + Recharge Batteries

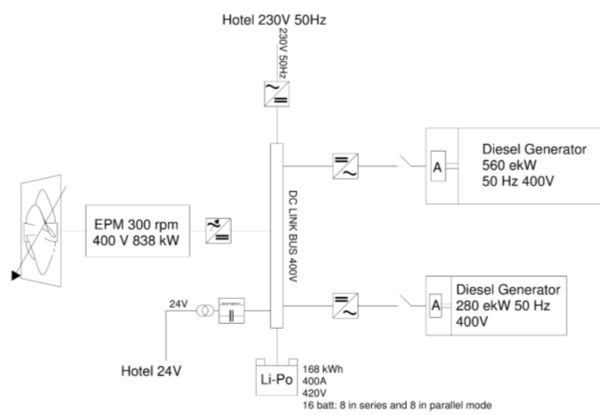

Figure 9. Layout of the full electric proposed propulsion plant.

6 CONCLUSION & RECCOMENDATION

The paper presented a methodology to assess, in an original way, the energy propulsion efficiency. The methodology was applied to a real case study for the validation through dedicated sea trials. By using the presented methodology, a new hybrid propulsion system has been designed with the aim to improve the ship's energy efficiency.

The proposed design, after the careful analysis of the different operating profiles of the ship, lead to a particular configuration of the generation system, "*Father & Son*" which refers to an asymmetrical sizing of the diesel generators, whence the name. This solution gives a great flexibility to the plant and allows using the thermal engines near their optimum working point.

The main idea behind this work is to develop a tool that can help the designer in the early design phase. The correct use of this tool helps to reduce the environmental impact of a propulsion ship system, by reducing both emissions and fuel consumption.

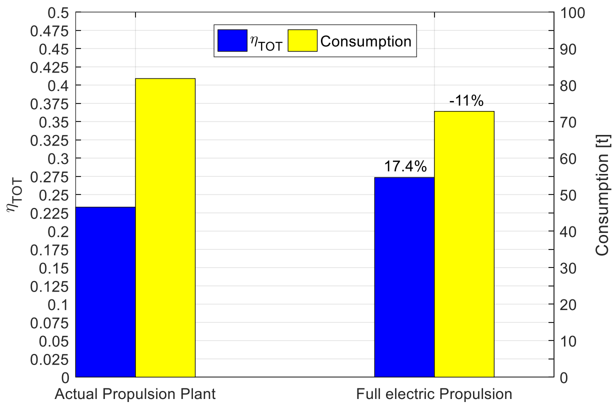

Figure 10. Saving, in terms of fuel and energy, of the proposed propulsion plant.

As shown in Figure 10, installing the new hybrid propulsion system, design by using the developed numerical code, the annual fuel saving could be around 11% and consequently an increase in energy efficiency up to 17%, compared to the actual propulsion system. These values could decrease because actually, the losses due to the electrical transmission are not taken into account (from literature they should be 2-4%)

The study carried out is not only applicable to the specific case of "G. Dallaporta", but to a wide range of working and research ships.

When the propulsion system deals with different design speeds or very different propulsive loads, such as harbor and escort tug, supply vessels, anchor handling, etc., the choice of an asymmetrical power generation could give the best advantages.

Further studies will address the auxiliary and deck systems in order to include them in the energy assessment methodology. In addition, the development of a suitable power management system will be a crucial task to manage the correct machinery switch between the different propulsive modes.

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