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Environmental and operative impact of the electrification of a double-ended ferry

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Abstract— **The increasing sensibility to the environment protection and emission reduction in the atmosphere is also influencing the maritime shipping. The more restrictive regulations on pollutants suggest the adoption of alternative onboard propulsion and energy generation systems. To this end, electrification is a promising solution for pollution reduction, giving some flexibility on the strategy to use for the onboard system. Moreover, a hybrid-electric system can be combined with the exploitation of green fuel, increasing the potential reduction of total emissions. However, the final efficiency, both in term of emission reduction and expected operative expenditure, is strongly influenced by the operative profile of the vessel. This is of utmost importance both in case of a newly designed vessel and in the retrofitting of an existing one. In the present work, the impact of electrification on a double-ended ferry is presented, taking into consideration the operative profile of the vessel derived from real navigation data.**

Keywords— Hybrid ship propulsion, energy storage system, shore connection, ferry, integrated power systems, CO_2 emissions.

I. Introduction

Maritime shipping is currently the most environment-sustainable mean of transporting cargo and passengers worldwide [1]. Still, one of the main concerns in marine sector is the reduction in the ships' pollutant emissions. At present, the focus is mainly given to the reduction of pollutants inside harbor and coastal areas, where vessels manoeuver and sail at slow speed [2]. Such operative conditions make the engines operating far from their optimal working point, leading to an increase in pollutant emissions in respect to the open sea sailing. Being the ports usually built near, or even into, urban areas, and given the presence of several urban areas on the coast, it is evident why the reduction of emissions in these areas is mandatory in the new Smart Cities paradigm [3]. In a world more and more aware about environmental issues, and recognizing the impact of pollution on people health, also regulatory bodies in marine sector enforce restrictive international regulations on marine pollutions [4]. These new rules are forcing the shipping industry to adopt "green" solutions for the new vessels, or to refit the propulsion system of the existing ones to improve their sustainability and reduce their environmental impact [5]. To achieve such goals, at present three strategies are technically feasible [6]. The first option is to use an ecological fuel for supplying the main and/or auxiliary engines [7,8]. The second option is to install onboard equipment dedicated to the exhaust gas treatment. The third option is to rely on the vessel's electrification [9-12]. In this context, the INTERREG project METRO (Maritime Environment-friendly TRanspOrt systems) analyzes innovative solutions to improve the North Adriatic maritime transport environmental sustainability. Specifically, a team composed by Universities, companies, and public bodies work towards defining a more efficient, sustainable and integrated transportation network between Italy and Croatia.

In this paper, part of the project results are depicted. In particular, a study is proposed, referring to the electrification of a double-ended ferry. Three configurations for the refitting of its propulsion system are investigated, comparing them with the conventional one in terms of pollutant emissions, consumables needs, and costs. In section II the methodology applied for assessing the environmental and operative impact of the vessel is presented. Section III presents the specific vessel in study, its route, as well as the new ship configurations. Finally, Section IV discusses the results, followed by the Conclusions.

II. Methodology for the Analysis

In order to evaluate the performance of the different machinery configurations the so-called Data Driven Design approach has been applied. The optimal sizing of

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a hybrid propulsion system depends upon the actual operating modes of the ship, as well as upon their sequence. Thus, a methodology able to tackle these factors is needed, optimizing the propulsion system upon the specific vessel or fleet operation. The developed methodology, outlined in Fig. 1, is composed by the following sequence of design stages.

- Input data collection, composed by historical *navigation data* (latitude, longitude, heading and speed) and technical *installation data* (e.g. engine installed, trial and service speed) of existing vessels on the route in analysis;
- *Data cleaning and enrichment*: raw input data is cleaned from possible errors and additional information is added (such as sailing condition or mission/legs information);
- *Average mission selection*: initially the input data are split into several *missions*. An average operating profile is derived for each mission group. Indeed, given the highly repetitive pattern of some ships, a statistical algorithm can be used to obtain a mean route from the input data.
- *Operating mode extraction*: for each mission the sequence of the operating modes during sailing condition is extracted using machine learning algorithms, in order to identify maneuvers and crossings average duration and power. The time spent in port is assessed by means of statistical analyses compared with the available timetables.
- *Simulation*: a simulation tool, developed by Wärtsilä, makes it possible to evaluate the fuel consumption, the pollutant emissions, the OpEx (Operational Expenditure) and the TCO (Total Cost of Ownership) per each tested configuration.

The proposed methodology relies on historical navigation data, as well as technical details of existing vessels. Thus, considering an existing route, the method is suitable for the design of a new vessel or for the refitting of an existing one. It is possible to apply this approach also to a new route, or to a new use for an existing route. In fact, the input data can refer to vessels sailing on similar routes, as well as to a set of navigation data extrapolated from navigational, meteorological, and oceanographic analyses. In case ship owners provide a specific operating profile composed by sequences of conditions in determined time lapses, the process may start directly from power profiles simulation.

III. Vessel Operative Profile and Propulsive Configurations

A. Baseline ship

In the present study, a reference ship and route have been used as the baseline case study. Then, the benefits of the proposed new configurations in terms of consumptions, emissions, and costs have been assessed by means of the methodology depicted in the previous Section. The case study ship is a bidirectional ferry: a vessel that performs multiple voyages on the same route. For this purpose, the vessel is equipped with two separate propulsion systems, one at each vessel's ends, that both operate during the travel at two different loads. Such systems operate also as thrusters, during the maneuvering in port. The ship's main characteristics are depicted in Table 1. It operates between the ports of Porozina and Brestova (Croatia), on the North Adriatic Sea coast (Fig. 2). The 2.7 nautical miles long route takes approximatively 35 minutes (15 minutes of sailing at 11 knots, plus 10 minutes of maneuvering at each port), and then the ship remains at berth for 15 minutes. At night, the ship is berthed for a 4-hour long period. These phases compose the *missions* of the vessel.

The reference ship is equipped with a conventional Diesel propulsion system, and has two additional Diesel generators for supplying the other onboard loads. The hotel load is nearly constant in each operating condition (maneuver, port, or navigation) at nearly 80 kW. Conversely, the propulsion power directly depends on the operating condition, as well as on the sea state. In order to attain the reference data for designing the propulsion system, an analysis on the navigation data has been done, to obtain a medium daily profile. This has been achieved by collecting the position and the speed on the sample route with an average sampling rate of 5 minutes, in a period from 1 Jan. 2016 to 1 June 2019.

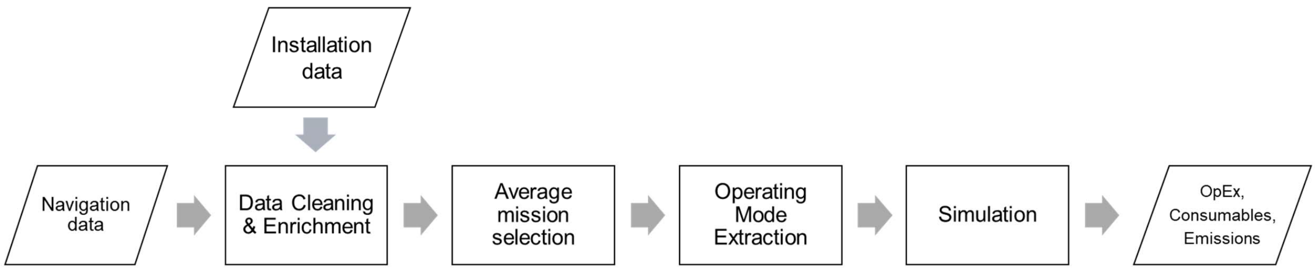

Fig. 1. Methodology applied

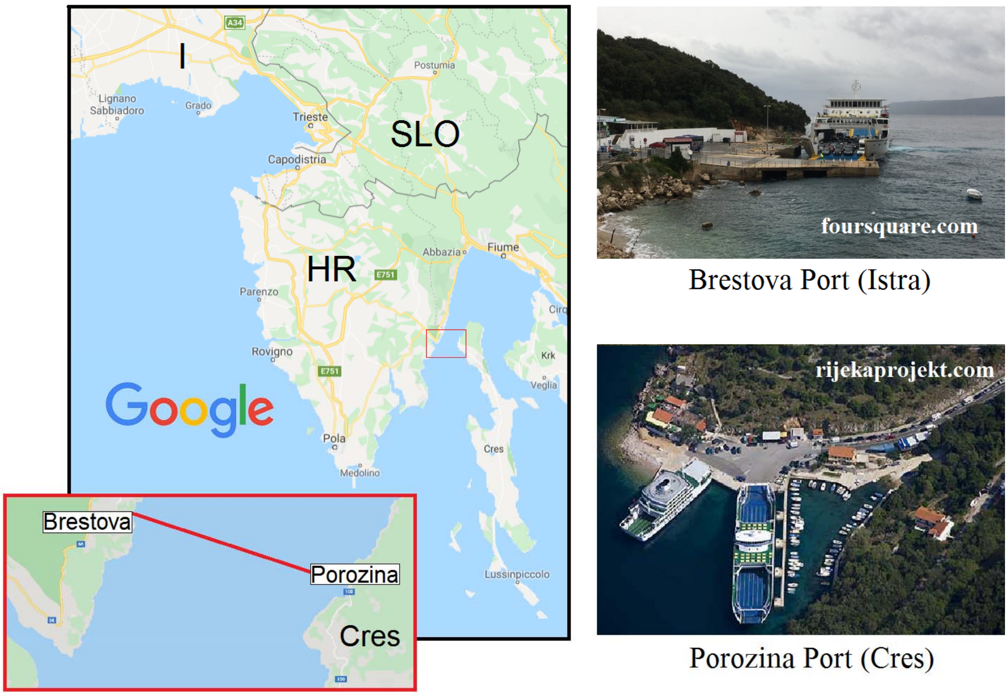

Fig. 2. Reference ship route

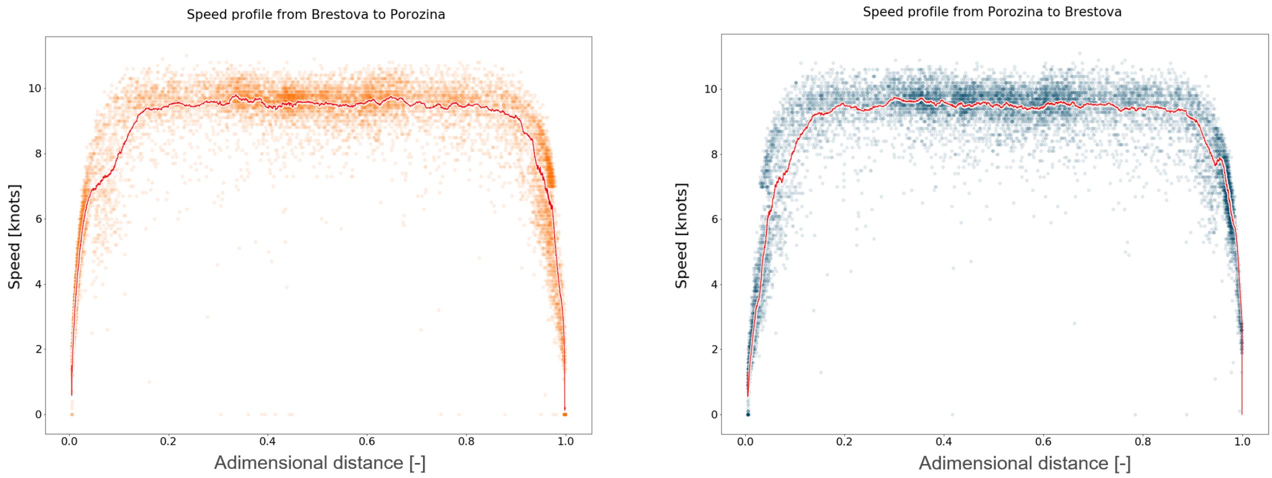

Fig. 3. Baseline ship speed profiles (dots: single data points; line: mean route)

TABLE 1: BASELINE SHIP MAIN CHARACTERISTICS

Length overall	94.5 m
Breadth	20 m
Draught	2.3 m
Gross Tonnage	2330 GT
Deadweight	1.000 t
Year	2006
Capacity (vehicles/passengers)	176 / 600
Engines	2 x 800 kW
Gensets	2 x 135 kW
Speed (max)	12 kn

TABLE 2: SHIP CONFIGURATIONS

	DM	***PH***	***SH***	***SHDF***
Diesel propulsion engines	2 x 800 kW	2 x 800 kW	-	-
Gensets	2 x 135 kW	2 x 135 kW	2 x 800 kW	2 x 1110 kW
Shaft generators	-	2 x 200 kW	-	-
Electric propulsion motors	-	-	2 x 800 kW	2 x 800 kW
Shore connection	-	-	750 kW	670 kW
ESS	-	750 kWh	750 kWh	750 kWh
Fuel	LFO	LFO	LFO	LNG

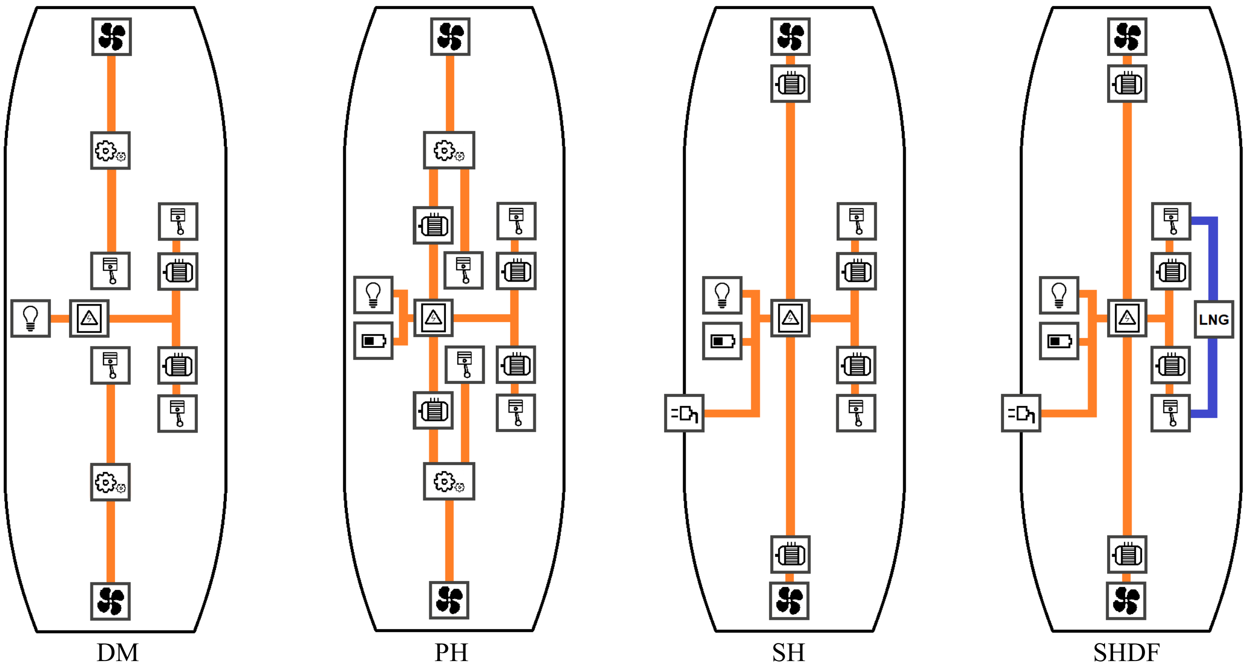

Fig. 4. Ship configuration considered.

The data resulted in a total of nearly 125 thousand samples, allowing to define the real ship mean speed profile with a good accuracy (Fig. 3). From the obtained speed profile, it is possible to distinguish between pure propulsion mode, maneuvering and stationing in port. Then, the speed-power relation curve of the vessel allows assessing the average propulsive power needed for each travel. The loads absorbed during the other operating modes are design assumptions determined according to the ship operators' feedback. From the speed profile recording, it is also possible to determine the number of missions performed during a working year. The extraction of the ship's operative profile, with the associated levels of average absorbed power in the different operating modes and the number of missions per unit of time, are useful data to define the size of the machinery in the proposed configurations.

B. *Configurations in study*

In the present study, the following configurations (Fig. 4) have been analyzed and compared:

- *Conventional diesel mechanic propulsion (DM)*: the baseline configuration of the vessel, with segregated Diesel propulsion and electric power generation system.
- *Parallel hybrid configuration (PH)*: hybrid configuration, with two Diesel engines and two electric motors for propulsion, and an integrated electric power system with Diesel generators and energy storage system. The electric motors can operate also as shaft generators during the navigation if the main Diesel propulsion engines are used.
- *Series hybrid configuration (SH)*: hybrid configuration with electric propulsion, an integrated power system with Diesel generators, an energy storage system, and a shore connection.
- *Series hybrid with dual fuel engines (SHDF)*: equivalent to SH but with dual fuel engines.

The three new ship configurations have been designed by defining the power of the Diesel engines, the generators, and the shore connection, as well as determining the Energy Storage System (ESS) size. The resulting machinery data is shown in Table 2, along with the baseline ship configuration (DM).

IV. Results and Discussion

By means of the method presented in Section II, the analysis of the ship operation has been done, comparing the baseline ship with the three new proposed configurations. In particular, along with the ship's daily operational profile, a set of assumptions have been made for the fuel costs and related pollutant emissions, as well as the additional consumables needed by the ship and the energy cost for the shore connection. The related data is shown in Table 3 for the Fuels. For what concerns the electricity costs, it has been set a shore power price equal to 80 €/MWh. The result of the statistical analysis performed in the *average mission selection* step of Fig. 1 is shown in Fig. 3, in terms of ship speed in respect to the sailed distance. The several different dots on Fig. 3

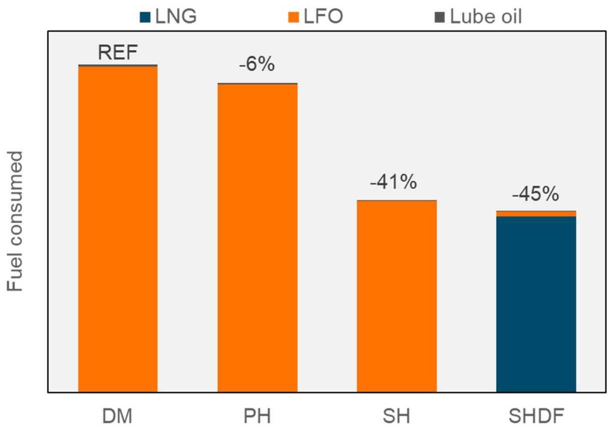

Fig. 5. Annual consumables in weight for the configurations considered (LNG: liquid natural gas; LFO: light fuel oil)

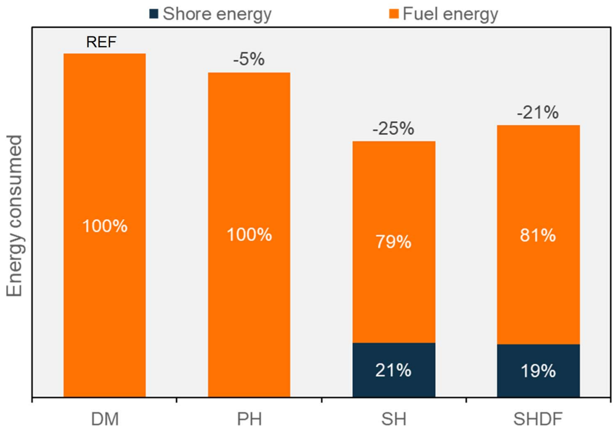

Fig. 6. Annual energy consumption.

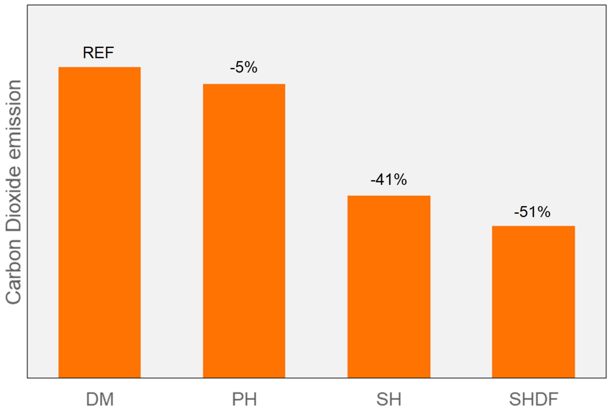

Fig. 7. Annual Carbon Dioxide emissions in weight.

TABLE 3: CALCULATION ASSUMPTIONS - FUEL

	Cost [€/ton]	*LHV [MJ/kg]*	*Sulphur [%wt]*	*Carbon [%wt]*	*Sep. Losses [%wt]*
LFO	450	42.70	0.2%	86%	0.5%
LNG	400	49.20	0%	75%	
Lube Oil	2300				

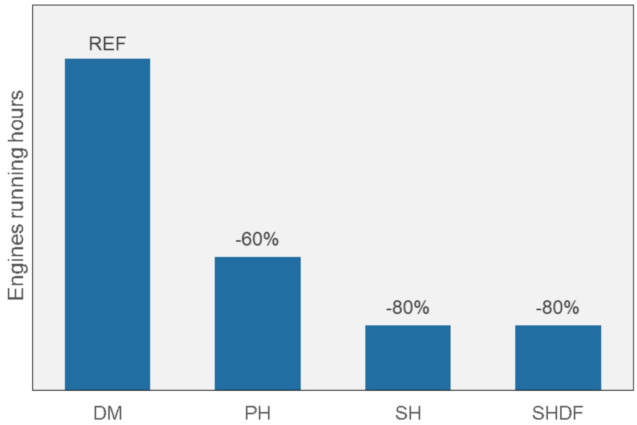

Fig. 8. Annual engines running hours.

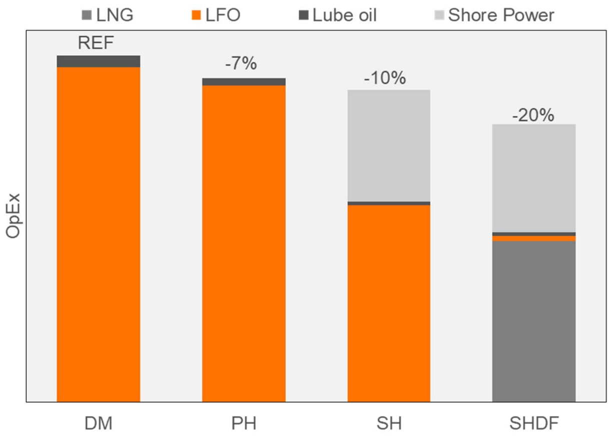

Fig. 9. Annual OpEx (Operational Expenditure).

are the speeds of the ship, measured on the baseline route during the recording time. Conversely, the continuous line represents the extracted mean speed profile on the route. The results of the analysis are depicted in the Figures 5 to 9. Specifically, Fig 5 shows the amount of consumables used in an entire year in terms of LFO (Light Fuel Oil), LNG (Liquid Natural Gas; for the SHDF configuration only), and Lube oil. The amount of the total electrical energy supplied by the shore through the shore connection (dark blue), and by the engines (orange), is shown in Fig. 6. Conversely, the aggregated running hours for the onboard Diesel engines (including both propulsion and electrical generation in DM and PH configurations) are depicted in Fig. 7. The total carbon dioxide emissions have been also calculated (Fig. 8), excluding from the study the CO_2 related to the electric energy supplied by the shore (which depends on how such electric energy is produced). Finally, on the basis of the prices depicted in Table 3, an evaluation of the expected OpEx has been done (Fig. 9).

As can be clearly seen from Fig. 5, for the analyzed case, all the hybrid solutions enable fuel consumption savings, starting from 6% in weight and reaching up to 45% when the shore connection is used for supplying the onboard batteries. Obviously, a suitable shore infrastructure is needed, to provide the required power to the ship during berthing, which is approximately 20% of the total energy consumption for the analyzed case (Fig. 6). Since the CO_2 emissions are directly proportional to the fuel consumption, in Fig. 7 a trend similar to the Fig. 6 one can be seen. In this sense, LNG fuel in combination with batteries assures up to 10% savings in respect to SH configuration. Moreover, all the hybrid solutions enable a significant reduction of engines running hours (Fig. 8), thus lowering the engines' maintenance cost. Remarkable performances can be underlined for both the SH solutions, thanks to their high flexibility. In conclusion, Fig. 9 shows a significant reduction of the OpEx, thanks to the additional electrical subsystems. In fact, while the OpEx for DM and PH configurations depends only on the consumables cost (since maintenance costs have been neglected in this study), the shore electricity costs have a significant impact in the other two configurations. The latter is often the key factor to make such solutions feasible from an economic point of view.

V. Conclusion

In this paper, the redesign and the analysis of a ferry has been proposed, by using a methodology able to take into account several different aspects of the ship design. In particular, the applied method relies on statistical analysis of existing ships and routes, to obtain a usable mean operating profile for the ship to be designed. Then, by means of proprietary algorithms, it has been possible to analyze the results obtainable by different vessel's configurations. In particular, a comparison in terms of consumables, annual energy consumption, annual CO_2 emissions, engines running hours, and OpEx have been made, and presented. It is evident that some of the results, and consequently the appeal given by one solution in respect to another, depends also on parameters that have been ignored in this study. As an example, the CO_2 emissions related to the electrical energy supplied by the shore to the ship has not been evaluated. This has been done because such a parameter strongly depends on the port electricity contracts (which can include different quota of renewable energy sources) and on the possible presence of renewable energy sources in the port (like photovoltaic or wind generators). Actually, this is proving to be an issue in the marine sector just like in the automotive sector, where the real impact of electric cars cannot be assessed without analyzing the specific energy mix of the electricity grid on which the recharge stations are connected. In this regard, the research here presented is part of a wider research program, which is aimed at analyzing and proposing solutions for the green maritime transportation in the Adriatic area. The focus of such a project is wide, including not only the ships, but also the ports power systems, the specific routes and passenger/goods flows. By means of such an integrated approach, it will be possible to have a clearer vision about these topics, as well as to propose a solution including all the elements, specifically tailored for the needs of the single route.

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