A zero-emission ferry for inland waterways

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Abstract. Reducing the human environmental impact is one of the most critical issues nowadays: in this perspective, the progressive decommissioning of fossil fuels is a significant priority to guarantee a sustainable future for the next generations. This paper proposes a zero-emission ferry for inland waterways and short-sea navigation, focusing on realistic solutions to provide the best trade-off between operational performance and environmental sustainability. In particular, the object of this study is the refitting of a double-ended ferry working in the Lago Maggiore, one of the largest Italian lakes. Systems suitable for the purpose have been selected and integrated onboard to maximize efficiency, implementing full-electric propulsion with electric motors, a Li-ion battery storage system, and photo-voltaic panels. The benefits and drawbacks of the considered technologies have been evaluated to select the most promising design solution, focusing on both onboard and on-shore impact in terms of compatibility with the existing infrastructures and considering life-cycle sustainability.

Keywords. Zero-emission ship, Green ship, Sustainability, Electric ferry, Energy storage systems, Electric propulsion

1. Introduction

The United Nations World Commission on Environmental and Development has firstly defined Sustainable Development as a “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” [1]. In this context, the emission of pollutant gases in the atmosphere is recognized as an urgent problem. While the researchers are looking at alternative fuels to guarantee a sustainable future for the next generations, the regulatory frameworks are pushing toward implementing sustainable strategies in all industrial fields, focusing on a massive and constant reduction of greenhouse gas emissions. In particular, reducing environmental pollution is one of the primary drives of the International Maritime Organization (IMO) in issuing regulations. The MARPOL Annex VI rules the emission of the main air pollutants con-

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tained in ship exhaust gases, such as sulfur oxides (SO_x), nitric oxides (NO_x), and carbon dioxide (CO_2).

Within this regulatory framework, the maritime world is trying to react by introducing new technological solutions. [2] presented a perspective view of the impact of the increased environmental awareness on the future of the shipping world. Electric propulsion has been identified as one of the most promising technological solutions to guarantee a sustainable and economically effective future for maritime transport [3,4,5], with a particular focus on hybrid systems including zero-emission technologies such as batteries and fuel cells[6]. Case studies and applications of fuel cells to ferry and passenger ships have been presented in recent literature [7,8]. Battery systems are the most promising technological solution for shipboard applications, especially in hybrid configuration [9,10,11], also coupled with solar panels [12,13]. The Yara Birkeland [14] and E-Ferry Ellen [15] projects successfully adopted a full-electric battery-based propulsion system without a thermal engine onboard.

This paper presents the refitting of a double-ended ferry working on the Italian lake Lago Maggiore, considering advanced technological solutions to meet zero-emission requirements. In particular, the focus of the work is to study an alternative propulsion system to replace the main diesel engines and generators with a full-electric zero-emission propulsion and generation plant relying on batteries and photovoltaic panels. The design process accounts for the specific requirements of the refitted ship. The paper discusses the propulsion system design procedure starting from the data of the original ship, with a particular focus on the sizing of the battery pack based on the analysis of the operating profile. Eventually, a comparison between the original and refitted ship is provided and discussed.

2. Reference ship

2.1. General description

The Ticino Ferry is a 54m long double-ended ferry, with a load capacity of 33 vehicles and 844 passengers. Table 1 summarizes the ship's main data. The ship was built in 1996 by Cantiere Navale Ferrari, features a traditional diesel propulsion system, including two diesel engines, each moving one azimuthal thruster via a reduction gear. The propulsion machinery is located at the aft and fore of the hull: according to the ship crew, during navigation, the aft propeller delivers most of the required thrust, while the fore propulsion system contributes a small amount, mainly for maneuverability reasons. On the comeback trip, fore and aft are switched, and so are the propulsion systems. Each

Table 1. Technical data of the reference ship "Ticino"

Lenght	54.22 m
Displacement	558.9 t
Main propulsion	2×533 kW Diesel Eng., 2 azimuthal thrusters
Electric generation	2×162 kW Diesel geneators
Speed	11.5Kn Design, 13Kn Max.
Total capacity	844 passengers, 33 vehicles

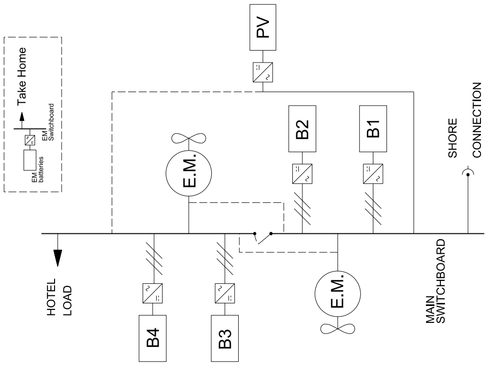

Figure 1. Layout of the proposed propulsion system

engine delivers 533 *kW* at 1800 *rpm*, allowing a design speed of 11.5 *kn*. Two 162 *kW* diesel generators ensure the electrical power for the hotel load.

2.2. *Operating profile*

The typical mission of the case study ferry is a trip between the ports of Intra and Laveno on the Italian lake Lago Maggiore. Each trip takes around 30 minutes at the design speed and is broken down as follows:

- A maneuvering phase of about 1 minute to leave the departure dock;
- A navigation phase of 18 minutes;
- A maneuvering phase of 1 minute to approach the arrival dock;
- A dock stop of 10 minutes, to allow the passengers and vehicles to disembark and embark.

Notice that the maneuvering phase is relatively fast because of the double-ended configuration of the ferry. The ferry's daily routine consists of 20 round trips per day with a lunch-break of 60 minutes in the middle, for a total of 10 working hours divided into two sessions.

3. Zero-emission refitting

3.1. *Propulsion and generation layout*

The refitting of the presented ship is inspired by a zero-emission design philosophy and features full-electric battery-powered propulsion without diesel generators on board. The refitting is intended to keep the same double-ended propulsive configuration of the existing ferry, targeting the machinery and other energy-expensive features to enhance the overall efficiency.

Figure 1 shows a layout of the concept propulsion plant. The batteries are split into four packs to increase the redundancy and are connected to two main switchboards. Such a symmetrical layout allows for keeping the trim straight. Each electric motor is con-

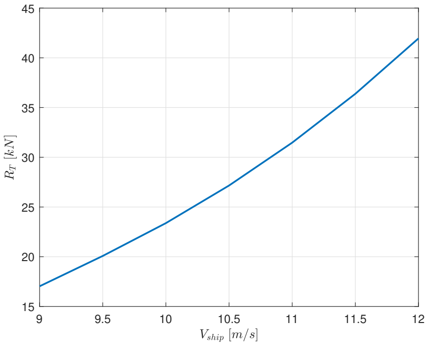

Figure 2. Towing resistance curve estimated via systematic series.

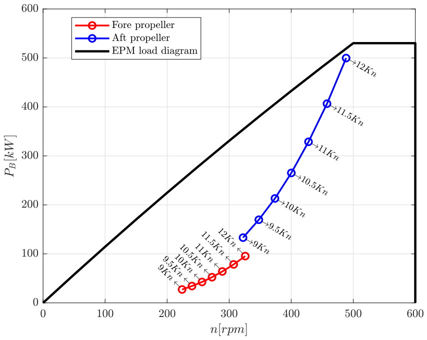

Figure 3. Engine-propeller matching with the electric propulsion motor

nected to its nearest switchboard; however, a redundant connection to the other switchboard is ensured. Eventually, a photovoltaic (PV) system provides additional power by exploiting solar energy.

3.2. Propulsion motors

The main idea of the presented refitting is to replace the original diesel propulsion engines with two electric motors powered by battery packs while keeping the same azimuthal thruster, propellers, and service speed, to maintain the same daily schedule.

A towing test based systematic series for double-ended ferries [16] allowed assessing the resistance curve to evaluate the power and speed of the motors. Figure 2 shows the estimated total hull resistance, including a 10% service margin to account for fouling and rough weather conditions. For the open water characterization of the propeller, reference has been made to an equivalent Wageningen B-series propeller.

In order to select the proper electric motors, the load sharing policy between the fore and the aft propellers should be taken into account. According to the vessel crew, the ferry mainly relies on the aft propulsive line, yet it is common practice to exploit the fore propeller to deliver a small fraction of the total thrust for maneuverability reasons. Based on the information from the crew, the refitted propulsion system has been designed to operate on a hypothetical 80%:20% thrust sharing ratio between the propellers. Two Siemens HT-direct motors 1 FW4403-1HD three-phase synchronous permanent-magnet motors have been selected. The motors feature a nominal power of 530 *kW* and a nominal speed of 500 *rpm*, thus removing the reduction gears. Figure 3 shows the engine-propeller matching for both the aft and the fore propulsion drives according to the assumed load sharing policy.

3.3. Energy efficiency improvements

When designing a battery-powered ship, the energy efficiency of every single process on board is a significant concern, as the weight and volume of the batteries are limiting factors when maximizing the vessel range. In the considered refitting, some straightforward efficiency improvements not directly related to propulsion allowed reducing the number of batteries onboard.

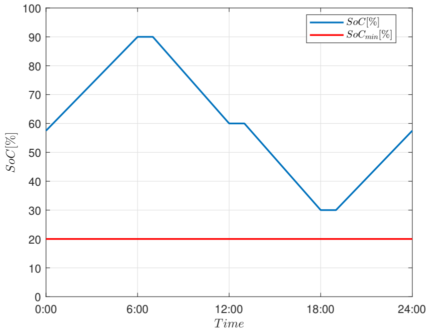

Figure 4. Daily energy profile without lunch break charge (Profile A)

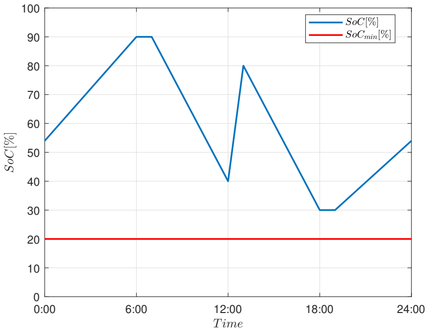

Figure 5. Daily energy profile with lunch break charge (Profile B)

Firstly, a renewal of the air conditioning system, including replacing the electric heaters with Air Treatment Unit, Chiller, and Fan-coils, led to an estimated reduction of the air conditioning electric consumption to one-third. Secondly, replacing the old generation bulbs with led bulbs has been estimated to be a 95 % reduction of the electric load due to lights on board. After the described interventions, the energy demand due to the electric loads during the mission has been estimated at 180 kWh.

Solar panels allow exploiting the sun energy to obtain free power when available, reducing the power required to the batteries. The adoption of solar panels has been evaluated based on the available surface on the upper decks, that allows the installation of 200 m^2 of panels, for a peak power of 44.8 kW, roughly equivalent to the hotel load. Because of the randomness of the solar energy, the PV panels have not been considered as an additional source when sizing the battery packs. However, it is worth mentioning that, considering the yearly average solar radiation on a flat surface in the region where the vessel operates according to models [17] and a 22.6% panel efficiency, the system is able to produce 62.3$MW/year$ of clean energy.

3.4. Battery packs

The onboard battery system has been designed to satisfy all the propulsive and auxiliary energy demands without considering the PV panels. The ESS needs to be sized to provide the energy required for the ferry operation, considering both the power request and the available recharge power and time. A typical day of operation includes 10 hours of navigation split into two 5-hour sessions by a 1-hour lunch break. Two possible profiles can be identified. In the first profile (A), the shore connection provides the hotel power during the lunch break without charging the batteries. Alternatively (Profile B), an adequate shore infrastructure would allow a partial charge of the batteries during the lunch break. Figure 4 and Figure 5 show the two alternative energy profiles for solutions A and B, respectively, while Table 2 presents a point-by-point comparison. In both cases, the battery state of charge (SoC) should neither exceed 90% to avoid battery heating nor fall behind 30% for safety and battery life reasons. Overnight, the shore connection ensures the slow charge. During the lunch break, a charge rate of $0.5-C$ has been assumed for Profile B considering the existing shore electric infrastructure, as discussed in Section 3.5.

Table 2. Energy profile and battery sizing

	Profile A	**Profile B**
Energy spent for one trip	180 kWh	180 kWh
Energy spent between two charges	3600 kWh	1800 kWh
SoC before lunch break	60%	40%
SoC after lunch break	60%	80%
SoC minimum	30%	30%
Nominal capacity	6000 kWh (400 modules)	3600 kWh (240 modules)

Table 3. On shore network requirements to allow fast charge during lunch-break (Profile B)

Fast charge energy	1.44 MWh	Slow charge energy	2160 kWh
Fast charge power	1.44 MW	Slow charge power	197 kW
Fast charge C-rate	0.5	Slow charge C-rate	0.33

KOKAM High Energy battery modules for marine applications have been considered an example solution: each module has a 15.1 kWh nominal capacity with 129 kWh/m^3 and $119kWh/t$ volumetric and gravimetric energy density, respectively. In order to match the nominal energy requirements, Profile A and B require 400 and 240 modules, respectively. Considering the energy densities of the proposed solutions, a volume difference of 18.5 m^3 and a weight difference 20 t can be roughly estimated.

The energy storage system has been arranged in multiple modules to increase redundancy. In addition, an emergency battery pack connected to a dedicated switchboard above the bulkhead deck provides emergency power, in analogy with the requirement for emergency diesel generators. The worst-case scenario for the emergency pack features a complete failure of the standard battery system when the ship is close to the port with no shore connection (Laveno): the battery pack must provide enough energy to sail back to the other port.

3.5. On-shore charge system

Profile A requires a relatively low shore connection power. Figure 4 shows that the battery pack is recharged only during the night, while the shore connection ensures the hotel power during the lunch break.

Profile B can be demanding for the shore infrastructures, as it requires a relatively high C-rate charge during the lunch break (Figure 5). Table 3 presents a brake down of the power request to the shore connection in profile B. In particular, the ship needs $1.44MWh$ of energy during the one-hour lunch break, which is $1.44MW$ necessary to guarantee the $0.5C-rate$. On the other hand, the 11-h long slow charge requires only $197kW$ due to the lower battery capacity. Despite the high power demand, the necessary charge power might be feasible for the high power network feeding the railway station nearby the dock of Laveno, where the vessel spends the lunch break.

4. Comparison with the original vessel

The previous sections presented two possible refitting solutions depending on the energy expenditure and charge policy profile. Despite the shore-power demand challenge, Pro-

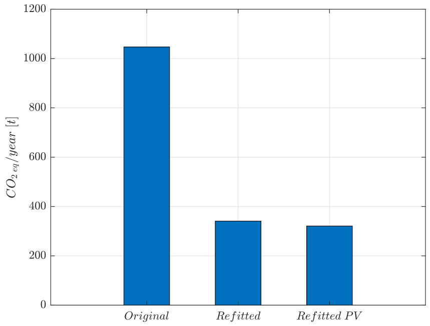

Figure 6. Comparison between the reference and the refitted ferry in terms of equivalent CO_2 emissions

file B has been evaluated as the most promising in terms of space and weight. This section compares the original vessel to the refitted vessel in case Profile B is assumed. From the weight point of view, the absence of fuel oil tanks compensates for the additional weight of the battery packs, resulting in a negligible weight difference at full load. From the emission standpoint, the refitted solution is intrinsically zero-emission, as it does not feature any thermal engine. However, to give a more rigorous analysis, the amount of equivalent CO_2 emissions ($CO_{2\,eq}$) has been compared, considering the emissions due to the production of the energy to charge the battery pack: the equivalent CO_2 accounts for all the greenhouse gases by converting them to the equivalent amount of carbon dioxide with the same global warming potential.

According to [18] the Italian national grid produces is 290 $gCO_{2\,eq}/kWh$. Considering that the ferry operates around 310 $days/year$, a working day of the ferry includes 20 missions which require 180 kWh each, and accounting for 5% losses due to the efficiency of the battery charging process, the annual emissions of the refitted ferry can be estimated in 341 $tCO_{2\,eq}/year$. Taking into account the PV panels leads to an extra 20 $tCO_{2\,eq}/year$ saving.

The same estimate can be made for the original vessel, considering the original propulsion and electric loads, leading to an energy consumption of 192 kWh per mission. The SFOC of the Diesel engines onboard is 217 g/kWh in optimal conditions. Moreover, the equivalent CO_2 emissions can be estimated in 4.06 $gCO_{2\,eq}/g_{fuel}$. Under the same operating conditions described above, the original ship produces 1047 $tCO_{2\,eq}/year$. Figure 6 compares the results in a bar plot: notice that, even considering the impact of the energy production toolchain, the overall environmental impact of the proposed solution is around one fourth of the original. Notice also that the contribution of the PV panels to the effectiveness of the system could be considered negligible.

5. Conclusions

This paper presented a double-ended ro-ro pax ferry refitting for lake navigation. The refitting has been inspired by a zero-emission philosophy, replacing the traditional diesel propulsion battery-powered with electric propulsion and photovoltaic panels. Two alternative solutions have been evaluated in compliance with the ship operating profile, with different energy profiles and charge policies. The most promising solution features a fast charge during the 1-hour lunch break. The required charge power is 1.44 MW and might be feasible after further evaluation of the existing local infrastructures. The refitting does not significantly impact the ship displacement, yet it effectively nullifies the local emissions and relies on a more efficient energy production tool-chain that reduces the impact from an overall perspective. Ultimately, additional benefits brought by the proposed refitting are noise reduction and lake livability improvement for residents and tourists.

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