Feasibility study of a hybrid-electric multipurpose craft for coastal sustainable navigation

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Abstract— **The importance of reducing polluting emissions of small crafts operating in coastal areas is also linked to the concept of preserving the marine and coastal environment. So, nowadays the need to reduce as far as possible the pollutants' emissions is a primary objective that must be considered in the design of any type of vessel. This paper illustrates the design of a small vessel conceived with two different operational conditions: passenger transport and research support unit. In particular, the hybrid-electric power system was designed to guarantee ZEM (Zero Emission Mode) navigation, even in protected areas where usually navigation is not allowed, such as natural reserves.**

Keywords— coastal navigation, sustainable mobility, modular design, multipurpose craft, hybrid-electric propulsion, Zero Emission Mode

I. INTRODUCTION

The reduction of polluting emissions is of primary importance in the marine field, also involving small vessels, used for public transport or work near the coast. The aim of these actions is to preserve the marine and coastal environment, but at the same time to encourage tourism by giving access to tourist places that were inaccessible by sea until now, such as the various marine reserves present in Italy.

The zones defined as coastal areas are characterized by a fragile natural ecosystem. This situation is particularly evident in the North Adriatic Sea, where lagoons, coastal areas, and natural reserves are present. To reduce pollution, vessels navigating within these specific regions must adhere to European Commission (EC) Regulations pertaining to the mitigation of pollution and noise emissions (Stage IIIA of Directive 97/68/EC). Other restrictive regulations concern emissions of NO_x, SO_x, and PM (particulate matter), although many smaller vessels do not comply with them. Eventually, in recent years the reduction of CO_2 by maritime transport has also become a primary concept. Dedicated studies [1] highlighted the impact of generated maritime pollution on the coastal area is about 20% of the total one and 17% of this is related to marine engines. It should be underlined that a large share of emissions relates to vessels moving at low speeds, for example, while a vessel entering the port [2] [3].

In order to reduce these emissions, fuel consumption, and noise, a hybrid-electric propulsion represents an interesting solution, particularly for small boats. Typically, the majority of applications utilizing this propulsion system are engineered and dimensioned with the primary objective of ensuring Zero-Emission (ZEM) navigation [4] [5]. This could allow the navigation of small vessels even in places where navigation is limited or prohibited, such as, in the framework of North Adriatic, the Miramare Reserve together with its Castle, encouraging sustainable tourism.

Therefore this article wants to illustrate the feasibility study of a multipurpose craft having a hybrid-electric propulsion, usable for navigation in the North Adriatic Sea, in particular in the Gulf of Trieste, with the aim of reducing emissions. In this way, the advantages given by both the shape of the hull and that of the propulsion system will lead to an integrated design, steered at maximizing the advantages of the ZEM [6]. Besides, the vessel shall be capable to perform multiple operations: passenger transport during the summer and support research activities during the winter.

The remainder of the paper is organized as follows: firstly, the peculiar environment where the vessel is supposed to navigate is analyzed to define the operational profiles. Then, a proper hybrid propulsion system scheme is selected to fit the design constraints and analyzed in detail to assess the performances in the operational environment.

II. ENVIRONMENTAL AND OPERATIONAL PROFILES

Usually, the concept of coastal navigation is completely detached from internal navigation [7], however, as demonstrated by the particular conformation of the North Adriatic coast, the two concepts are overlapping. The proximity between these two types of navigation means operating in two different conditions: open sea and restricted waters. The multipurpose vessel presented in this work can be used in the following configurations:

- Passenger craft for inland/coastal service;
- Research craft for marine-restricted areas.

Unfortunately, due to the conformation of the seabed throughout the Trieste area, the design of the vessel will have to take into account the water depth, which on average is around 10 meters, and the speed limits of navigation. In detail for the passenger transport service, the following navigation route (Fig. 1) was selected, as regards public transport:

- Molo IV (Trieste) – Barcola
- Barcola – Miramare Castle
- Miramare Castle – Santa Croce
- Santa Croce – Filtri
- Filtri – Portopiccolo
- Portopiccolo – Duino

Along the various sections of the route, there are limitations in terms of speed, which are shown in Table I. In particular, it must be taken into account that in the section where you will pass through the Marine Reserve of Miramare (Fig. 2), in ZEM mode navigation is mandatory.

The temporal and spatial parameters related to the route are determined using Navionics, an Italian company specializing in the production of nautical electronic cartography, as depicted in Fig. 2.

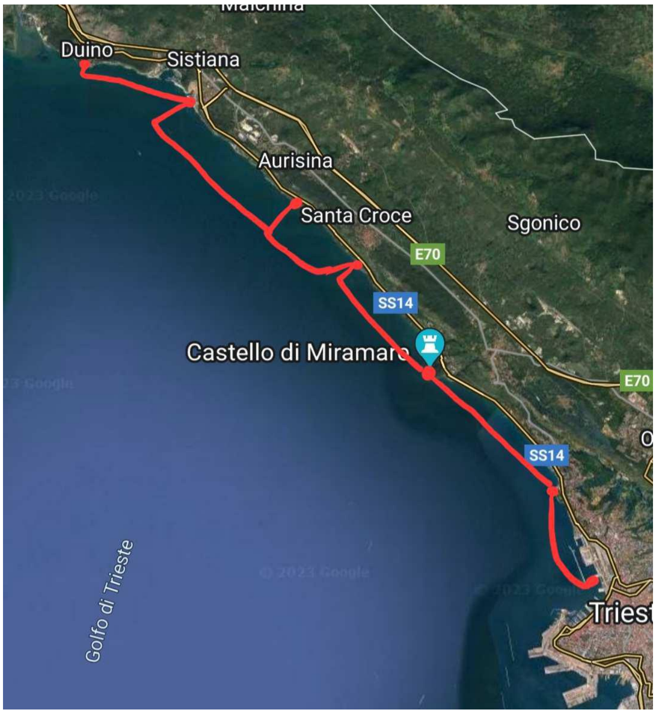

Fig. 1. Satellite map of Trieste with the route.

Fig. 2. Example of the little part of the route.

TABLE I. ROUTES CHARACTERISTICS.

Route	Distance [km]	Speed limit [knots]	Operative speed [knots]
Exit to the port of Triest	0.65	3	3
Navigation to Barcola	3	10	8
Entering the port	0.14	3	3
Exit the port	0.14	3	3
Arrival to Reserve	2.9	10	8
Entering the Castle	1.2	5	5
Entering the port	0.1	3	3
Exit the Reserve	0.25	5	5
Navigation to Santa Croce	2.5	10	8
Entering the port	0.7	3	3
Exit the port	0.7	3	3
Navigation to Filtri	2.4	10	8
Entering the port	0.7	3	3
Exit the port	0.7	3	3
Navigation to Portopiccolo	3.8	10	8
Entering the port	0.8	3	3
Exit the port	0.8	3	3
Navigation to Duino	3.2	10	8
Entering the port	0.2	3	3

III. HULL-FORM DESIGN AND HYBRID SYSTEM

To rate the application of a hybrid-electric propulsion system, capable of ensuring ZEM navigation, it is necessary a correct analysis of the hull forms. This has been adequately designed to perfectly adapt to the necessary hydrodynamic requirements [8], like low resistance level and a relatively small depth to allow accessing all the ports and marinas included in the route. These two antithetical requirements lead to a compromise hull shape as reported in [9]. The main characteristics are shown in Table II and Fig. 5, in the form of the general arrangements. The traditional propulsion included two shaft lines, which were however maintained with the hybrid system.

A hybrid propulsion system consists, on a general level, of a system capable of drawing the energy intended for motion from multiple components, forms of energy accumulated on board, which are usually an internal combustion engine (Diesel engine) and an electric motor powered from batteries. The hybrid systems can be classified into the various ways in which the components interact with each other, but basically, two principles can be adopted [10] to combine the electric engine and generators into an efficient and clean group:

- Parallel hybrid-electric configuration (Fig.3): where the electric motor and the diesel engine are both connected to the shaft line to reach full power. In this scheme, the mechanical coupling between the combustion engine and the propeller shaft is still present. Hence, both the internal combustion engine and the electric motor can drive the propeller in parallel. The allocation of power is delegated to the Gearbox, a mechanical device capable to transferring power from either the electric or endothermic engine to the shaft line. Additionally, clutches are usually fitted to disconnect either shaft line, electric motor, or diesel engine, enabling different possible configurations.

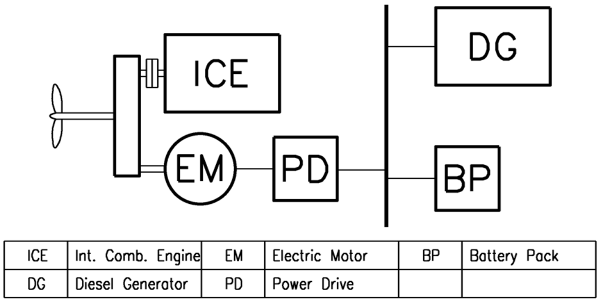

Fig. 3. Example of parallel hybrid-electric configuration.

- Series hybrid-electric configuration (Fig.4): where the electric engine alone takes care of the propulsion. There is no longer a physical connection between the internal combustion engine and the propeller shaft. In fact, the shaft is always driven by the electric motor, which in turn is powered by batteries on board to store the energy generated by the internal combustion engine. Therefore, in this solution, there will be two distinct energy sources that can be used for propulsion, the electric one (batteries) and the conventional one (Diesel engine).

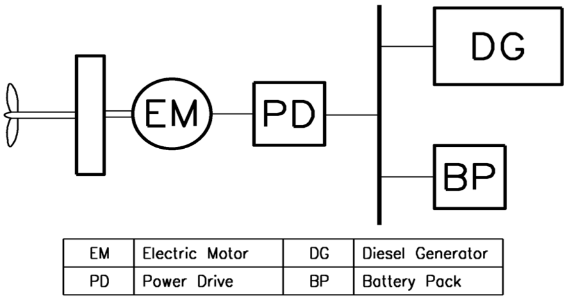

Fig. 4. Example of series hybrid-electric configuration.

TABLE II. MAIN CHARACTERISTICS OF THE MULTIPURPOSE CRAFT.

Length overall	L_{OA}	17.00	m
Waterline length	L_{WL}	15.58	m
Breadth	B	4.20	m
Depth	D	1.65	m
Draught	T	0.90	m
Displacement mass	Δ	23.15	t
Maximum speed	V_{MAX}	11.90	kn
Gross Tonnage, Italian national	GT	9.67	tsl
Crew		1	
Passengers		54	

To make an informed selection between these two categories of hybrid systems, it is imperative to consider their specific advantages and disadvantages. The series hybrid system has mainly two advantages, i.e. having to internal combustion engine connected to the shaft line, it can work in the most convenient regime, and it has a simpler transmission. On the other hand, the series hybrid has mainly three disadvantages compared to the parallel one: the required power must be supplied entirely by the electric motor; there are greater losses due to the conversion of energy from mechanical to electrical, followed by its subsequent reversion back to mechanical form; finally, this type of system is heavier. Despite these disadvantages, the hybrid-series propulsion system has been here chosen due to its superior capability in achieving ZEM navigation along the previously outlined route. In fact, this scheme can enable complete ZEM navigation, provided that an energy storage system of appropriate capacity is fitted onboard and onshore charging facilities are installed at one or more stops along the route.

IV. POWER BALANCE

To correctly size the hybrid propulsion system and the related electrical power system, the power required in the different operating modes shall be estimated. The relevant variability in propulsion power demand along the route can be primarily attributed to the coexistence of speed limits in restricted/sheltered waters near stops and the higher speed allowed during navigation in open water.

The speed limits established by the Port Authority are 3 knots for entering the port, 10 knots for navigation along the coast, and 5 knots for navigation in the Miramare Marine Reserve [11]. In this study, to cover all the possible operating conditions that the craft will encounter in its service life, these methods can be defined:

A. *ZEM at 3 knots*. For environmental and safety reasons, the navigation in the internal channels must be conducted at low speed.

B. *ZEM at 5 knots*. It is the specific navigation for Marine Reserve areas.

C. *ZEM at 8 knots*. It is the navigation speed chosen for the longest sections of the route. The decision was made not to exceed a speed of 10 knots in order to reduce fuel consumption and, consequently, extend the vessel's operational range.

D. *Navigation at 8 knots and battery charge*. In this phase, the generators are activated to recharge the batteries.

The users installed on board can be summarized in the following main categories:

1. Diesel engine;
2. Electrical propulsion;
3. Battery charger;
4. Outfitting (lighting, radar, bilge pump, navigation system, etc.);
5. Maneuvering system (rudders);
6. Air conditioning and engine room ventilation.

Considering the above-mentioned operational profiles, the influence of each user category has to be evaluated in the different operational modes in order to estimate the total power requirement of the vessel. The result of such an assessment is depicted in Table III, split into user categories. The total electrical power absorbed by the ship is shown as well.

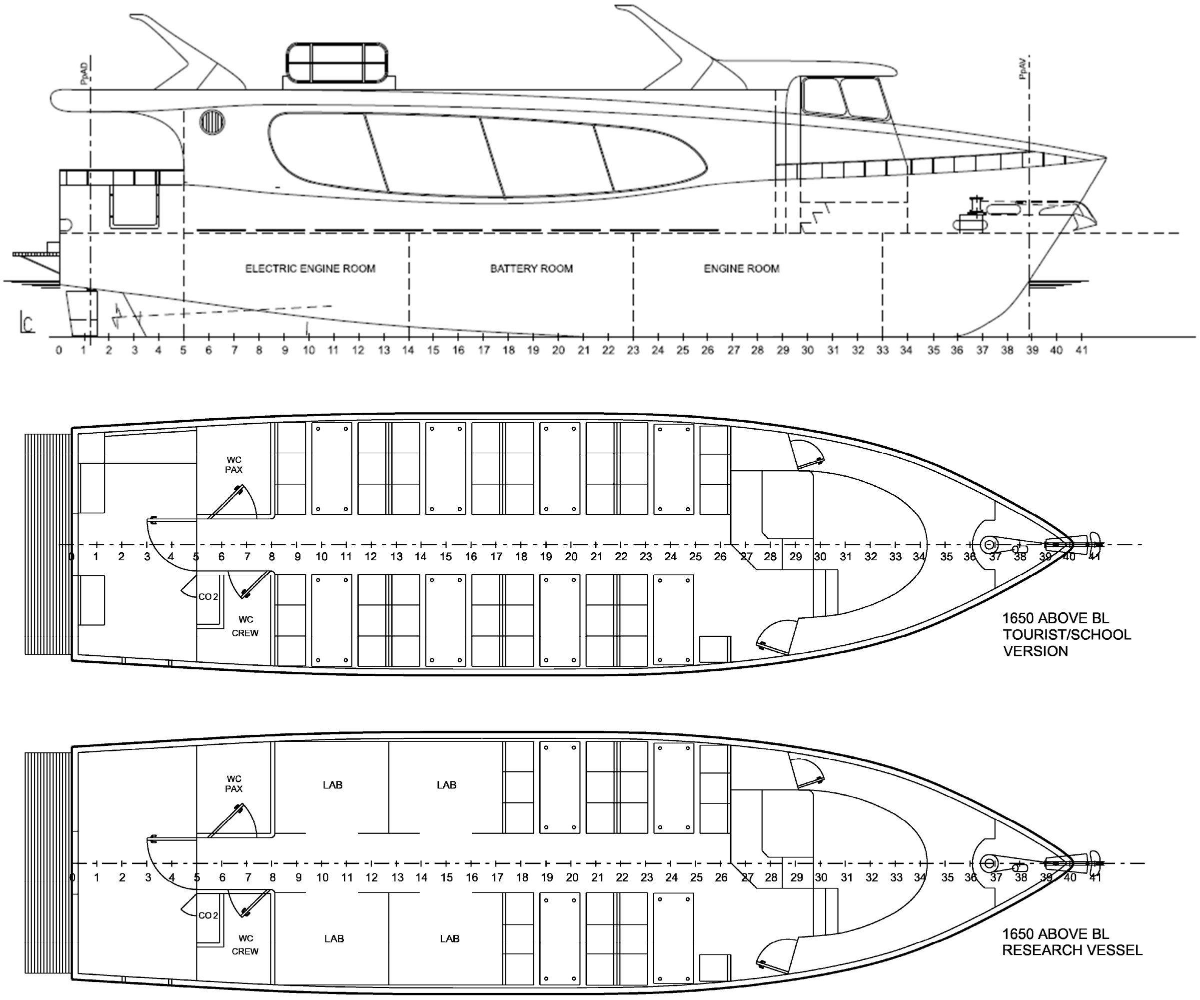

Fig. 5. General arrangement of the multipurpose craft

TABLE III. Power Balance for the Different Operational Profiles for Passenger Transport

	User categories (kW)						
	1	*2*	*3*	*4*	*5*	*6*	*TOTAL POWER RATED*
A	0	2	0	0.5	1	2	5.5
B	0	9	0	0.5	1	2	12.5
C	0	28	0	1	1.5	2	32.5
D	45	0	12.5	1	1.5	2	17 (batteries) – 45 (engine)

TABLE IV. Power Balance for the Different Operational Profiles for the Research Vessel

	User categories (kW)							
	1	*2*	*3*	*4*	*5*	*6*	*7*	*TOTAL POWER RATED*
A	0	2	0	0.5	1	2	8.08	13.58
B	0	9	0	0.5	1	2	8.08	20.58
C	0	28	0	1	1.5	2	8.08	40.58
D	45	0	12.5	1	1.5	2	8.08	25.08 (batteries) – 45 (engine)

On the other hand, if considered a vessel to support marine research, it becomes imperative to factor in the power requirements of the scientific instrumentation essential for the research study [12]. Therefore, given that the vessel is expected to traverse approximately the same route as the passenger transport craft and maintain the same navigation speed, Table IV provides insight into the overall power demands for each operational profile.

V. HYBRID- ELECTRIC POWER SYSTEM

The choice of a hybrid-electric propulsion system over a fully electrified system was imperative due to existing safety regulations that require the installation of an internal combustion engine. This engine must be available for activation in emergency situations, such as in the event of a battery pack failure. Furthermore, the internal combustion engine could be also useful for recharging the batteries while sailing at 8 knots if no onshore power supply is available. Table V provides the electric energy demand for the navigation along the previously described route including both the propulsion load and the other users' ones.

TABLE V. Total Energy in the Route.

Total energy in 3kn	5.57	kWh
Total energy in 5kn	4.07	kWh
Total energy in 8kn	39.05	kWh
Total energy (Trieste-Duino)	48.69	kWh
Total energy 2*(Trieste-Duino)	97.38	kWh

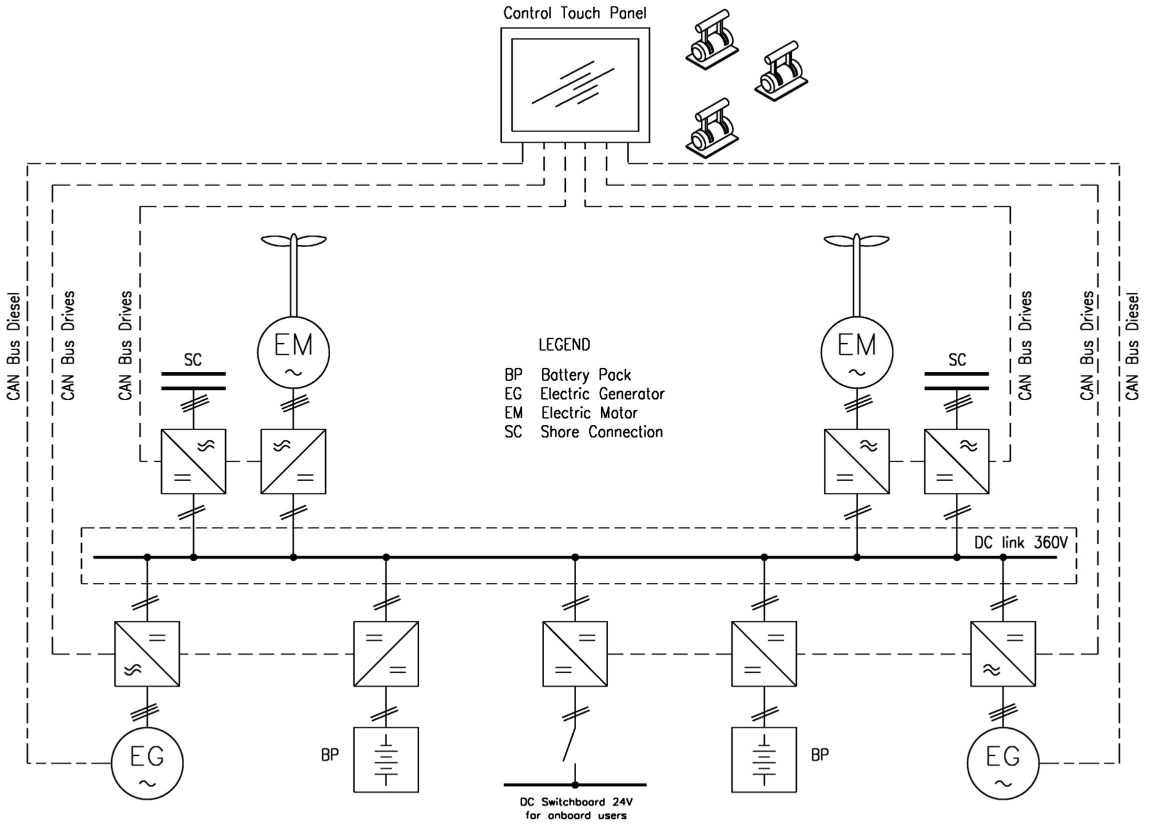

Fig. 4. Low Voltage DC Shipboard Power System.

It can be noted that at least of two battery packs having a capacity of 77.6 kWh shall be installed onboard in order to complete a round trip along the entire route in ZEM mode a single energy storage system facility. Navigation along the route takes about 2 hours and 30 minutes, while with two 77.6 kWh battery packs, the autonomy is over 3 hours of navigation at 8 kn. Therefore, it is feasible to establish a single charging station, that has been envisaged at the Trieste pier. The characteristics of the charging stations shall be carefully considered since have a strong impact on the recharging time and, thus, on the stop duration in Trieste [13]. On the market, three types of charging stations are available. In detail:

- Normal type 1: it is AC and works in phase at 220V or in three-phase at 380V; the craft is a public transport, so such a type cannot be taken into consideration, because it has to excessively long charging time of about 8-20 hours.
- Mode 3 type 2: it is the most used type in the industrial sector and includes a Schuko socket with five poles. This type has more reasonable charging times; in fact, four hours are needed to fully recharge the battery with a capacity of 77.6 kWh.
- Mode 4: it is in DC and is still under development; in fact, it has an earthing socket with two alternating poles and will be used exclusively for larger batteries. In this case, charging times are drastically reduced, it takes 30/45 minutes for a complete charge

The most obvious choice for the craft taken into consideration in this paper falls on the second type of columns, even if in the future the attention will certainly be shifted to the latter, but will be necessary for a total refitting of the onshore infrastructures.

Taking into account the environmental regulation of internal areas where the craft is intended to operate, a ZEM requirement is present. As the multipurpose craft design is powered by a hybrid shipboard power system, shown in Fig. 6. In particular, a Low Voltage DC (LVDC) distribution is conceived for easily recharging the battery packs, while feeding the electric propulsion motors. About this, it is considerable the presence of a shore connection plug, which allows for decrease further the craft's environmental impact on its area of operation [14] [15]. Such an advantage is achieved by offering a second source for recharging the batteries, in place of the thermal engines, so making the shore connection functionality an effective means to achieve the required green navigation. The shipboard power system will be described, together with interface power converters in the next paragraphs.

A. *Low-Voltage DC Distribution System*

The DC distribution represents the cornerstone for designing hybrid-electric power systems [16]. Following this concept, in the proposed case the central role is covered by a medium-voltage DC bus (rated voltage of 360 V), to which the shipboard subsystems are connected (Fig. 6). Focusing on the sources (highest section of Fig. 6), it is possible to observe the presence of the two battery packs (SP), the shore connection plug (SC), and the load (rudder motor and 24 V users). Whereas, the two electrical propulsion sub-systems can act as shaft generators driven by diesel engines, for recharging the batteries and/or feeding the onboard loads. Focusing on subsystems' sizing, a battery pack composed of

Lithium-ion cells (360 V, 228 Ah, and 79.2 kWh nominal energy, but 77.6 kWh) is installed to ensure the Zero Emission Mode navigation. Such a choice has been made taking into account the passenger craft configuration, as ensuring the proper ZEM range for the specific itineraries into restricted areas that the craft has to operate. In fact, the chosen capacity allows the ZEM navigation in all tracts, and the battery recharges through the SC when the ship is at berth.

During shore connection at berth, the maximum recharging power can be delivered to the batteries, while during navigation the recharge power will depend upon the other load's absorption. In fact, given the maximum electrical output deliverable by diesel engines (45 kW each one), the power used to supply onboard loads cannot be used to charge the batteries.

Finally, for what concerns 24 V DC users (e.g. air conditioning, engine room ventilation, outfitting), their rated power demand is 4.5 kW, whilst the electrical motor for actuating the rudder requests a maximum power of 2 kW.

B. *Interface Power Converters*

The interface converters are targeted at interfacing the LVDC bus with loads and sources (Figure 6). For guaranteeing the recharging functionality from the electrical land grid, interface converter 1 works as an isolated AC-DC converter, as it is constituted by an initial rectifier followed by an isolated DC-DC converter stage. This solution was adopted considering the relative advantages: galvanic isolation, weight/volume reduction, and high conversion efficiency. On the other hand, another interface converter acts as a DC-DC buck converter for supplying the 24V loads, whereas the DC-AC inverter supplies the rudder motor.

VI. CONCLUSIONS

The study is focused on developing a comprehensive design for a multipurpose craft capable of serving both as a means of passenger transportation and as a platform for marine research activities.

This craft was designed to operate in the North Adriatic Sea, where there are different environments as seen previously. Then, considering the operational aspect, it was possible to size the hybrid-electric power system, assuring the ZEM mode along the whole route of the craft under consideration. Therefore, the presence of this new propulsion system, together with an adequate system of battery packs and any newly developed infrastructures, allows the navigation requirements of the ship to be satisfied in ZEM mode.

In conclusion, this type of propulsion system allows you to comply as much as possible with the various existing regulations and at the same time encourage eco-sustainable tourism in the land and marine environment.

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REFERENCES

[1] M. S. Islam, and M. Tanaka, “Impacts of pollution on coastal and marine ecosystems including coastal and marine fisheries and approach for management: a review and synthesis,” *Mar. Pollut. Bull.*, vol. 48, fasc. 7–8, pp. 624–649, 2004.

[2] A. Łebkowski, “Reduction of fuel consumption and pollution emissions in inland water transport by application of hybrid powertrain,” *Energies*, vol. 11, fasc. 8, p. 1981, 2018.

[3] S. G. La, S. Mancini, L. Adelfio, and A. Giallanza, “Development of a Vessel Scheduling Optimization Model to improve Maritime Transport sustainability,” *Sustain. Futur.*, p. 100123, 2023.

[4] C. G. Biancardi, J. Kutcher, and R. Datla, “Low-Emissions of Small Crafts by Minimizing Hull’s Drag,” NAV 2012 17th International Conference on Ships and Shipping Research, 2012.

[5] D. Boote, and D. MASCIA, “Design Features of an Unconventional Passenger Vessel with Low Environmental Impact,” Ninth International Conference on Fast Sea Transportation FAST2007, Shanghai, China, 2007.

[6] U. la Monaca, S. Bertagna, A. Marino', and V. Bucci, “Integrated ship design: An innovative methodological approach enabled by new generation computer tools,” *Int. J. Interact. Des. Manuf. IJIDeM*, vol. 14, fasc. 1, pp. 59–76, 2020.

[7] V. Bucci, F. Mauro, A. Marino', D. Bosich, A. Vicenzutti, and G. Sulligoi, “Integrated design of a hybrid-electric power system for coastal-navigation multipurpose crafts,” 2017 Twelfth International Conference on Ecological Vehicles and Renewable Energies (EVER), IEEE, 2017, pp. 1–6.

[8] V. Bucci, F. Mauro, A. Marino', D. Bosich, and G. Sulligoi, “An innovative hybrid-electric small passenger craft for the sustainable mobility in the Venice Lagoon,” 2016 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), IEEE, 2016, pp. 1388–1395.

[9] A. Marino', and V. Bucci, “A simulation model for hybrid-electric inland waterway passenger vessels,” Technology and Science for the Ships of the Future: Proceedings of NAV 2018: 19th International Conference on Ship & Maritime Research, IOS Press, 2018, p. 388.

[10] D. Padolecchia, S. Utzeri, L. Braidotti, and A. Marino', “A Hybrid-Electric Passenger Vessel for Inland Waterway,” 2023 IEEE International Conference on Electrical Systems for Aircraft, Railway, Ship Propulsion and Road Vehicles & International Transportation Electrification Conference (ESARS-ITEC), IEEE, 2023, pp. 1–6.

[11] Ministero delle Infrastrutture e dei Trasporti - Capitaneria di Porto, “Ordinanza del Porto di Trieste -Risoluzione 43,” 19 agosto 2016.

[12] F. Mauro, U. la Monaca, C. Nasso, and V. Bucci, “An hybrid-electric solution for station-keeping and propulsion of a small coastal research vessel,” 2018 International Symposium on Power Electronics, Electrical Drives, Automation and Motion (SPEEDAM), IEEE, 2018, pp. 607–612.

[13] D. Bosich, A. Vicenzutti, and G. Sulligoi, “Environment-friendliness in Maritime Transport: Designing Smart Recharging Stations in North Adriatic Sea,” 2020 Fifteenth International Conference on Ecological Vehicles and Renewable Energies (EVER), IEEE, 2020, pp. 1–5.

[14] G. Sulligoi, D. Bosich, A. Da Rin, and F. Tosato, “An examination of mutual influences between high-voltage shore-connected ships and port earthing systems during phase-to-ground faults,” *IEEE Trans. Ind. Appl.*, vol. 48, fasc. 5, pp. 1731–1738, 2012.

[15] G. Sulligoi, D. Bosich, R. Pelaschiar, G. Lipardi, and F. Tosato, “Shore-to-ship power,” *Proc. IEEE*, vol. 103, fasc. 12, pp. 2381–2400, 2015.

[16] D. Bosich and G. Sulligoi, “Voltage control on a refitted luxury yacht using hybrid electric propulsion and LVDC distribution,” Eighth International Conference and Exhibition on Ecological Vehicles and Renewable Energies (EVER), IEEE, 2013, pp. 1–6.