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Electrification of a large catamaran water bus for everyday commuting in the Venice Lagoon

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***Abstract*— The continuous problem of environmental degradation caused by exhaust emissions in maritime navigation has prompted the search for sustainable solutions. One potential approach involves the development of innovative, environmentally friendly passenger boats that align with principles of ecological sustainability. The design process for such vessels demands meticulous consideration of the operational context and requirements. In regions with distinctive features like the Venice Lagoon, design alternatives must take into account the area's unique characteristics and comply with existing laws and regulations. This paper proposes a feasibility study on an innovative hybrid-electric catamaran water bus designed to both minimize wave generation and operate in Zero Emission Mode, aiming to properly address the mentioned environmental and navigation challenges.**

Keywords—Everyday commuting, hybrid-electric propulsion, Zero Emission Mode navigation, water bus catamaran, Venice Lagoon

I. INTRODUCTION

The Venice Lagoon epitomizes one of Italy's most exquisite and fragile landscapes, earning UNESCO World Heritage Site status in 1987. Due to its natural layout, all public passenger transportation services rely on an extensive fleet, detailed in Table I [1] [2], each distinguished by size and passenger capacity. Public transportation stands as one of the most influential sectors in the city life and economy, as demonstrated in Table II [3], and is currently experiencing a profound transformation in line with the Mobility 4.0 concept, addressing traffic congestion and inclusivity [4]. Furthermore, the COVID-19 pandemic has introduced additional challenges to urban living and public transit [5], particularly concerning the need to prevent overcrowding in confined spaces. Consequently, there has been a rising demand for smaller vessels to serve as water taxis over the past two years. The existing fleet in Venice consists of aging vessels lacking the latest advancements capable of minimizing both pollutant emissions and wave disturbance [6]. In this context, marked by an unmatched influx of tourists, the imperative of implementing sustainable policies for urban passenger transport cannot be overstated [7]. This aligns with the emerging trends supporting a more sustainable development of tourist accommodations [8]. A first solution consists in the application of hybrid-electric propulsion systems that reduces both air pollution and noise [9]. If tailorized, these technologies enable also Zero Emission Mode (ZEM) navigation [10]. However, for water bus, such systems must comply with stringent design constraints related to size and operational requirements. Water bus must exhibit exceptional adaptability to accommodate different passenger routes, as well as sea and weather conditions.

In this context, authors have concentrated on proposing the feasibility study of an innovative water bus expressly designed for everyday commuting inside and outside Venice's city center. A catamaran configuration has been chosen to minimize wave generation. Furthermore, authors proposed a tailorized hybrid-electric propulsion system in series configuration [11], effectively performing ZEM navigation in the majority of routes. Propulsion is assured by two electric motors, drawing energy from two battery packs. These solutions have consistently demonstrated exceptional performance in terms of travel duration and routes, successfully achieving the objective of ZEM navigation.

TABLE I. FLEET COMPOSITION IN THE VENICE LAGOON

Type of vessel	Approximate number
Ferry	150
Taxi and other public boats	450
Cargo vessel	1500
Pleasure craft < 10 m	26,000
Pleasure craft > 10 m	4000
Touristic passenger craft	150
Working unit	1200
TOTAL	**33,500**

TABLE II. 2013 – YEAR TURNOVER OF THE PUBLIC TRANSPORT IN VENICE LAGOON

Public transport		
	Total service	***Supplementary service***
Engine hours [h]	584,194	111,855
Revenue [€]	162,590,287	20,405,287

II. DESIGN CONSTRAINTS

A. Speed Limits in Venice Lagoon

Before delving into the technical aspects of designing an innovative water bus, the specific regulations mandatory for the Venice Lagoon must be taken into account. In this region, in addition to standard classification rules, certain unique local regulations significantly influence the design of boats addressed to public transportation purposes. Within this setting, issues concerning traffic congestion, the generation of waves by hulls, and the erosion of foundations and embankments have necessitated the imposition of strict speed limits for navigation.

In the Venice Lagoon, these speed limits are usually expressed in kilometers per hour, unlike the typical maritime practice of using knots as the unit of measurement. Fig. 1 illustrates the speed limits imposed in the major urban canals to provide a clear overview of these regulations.

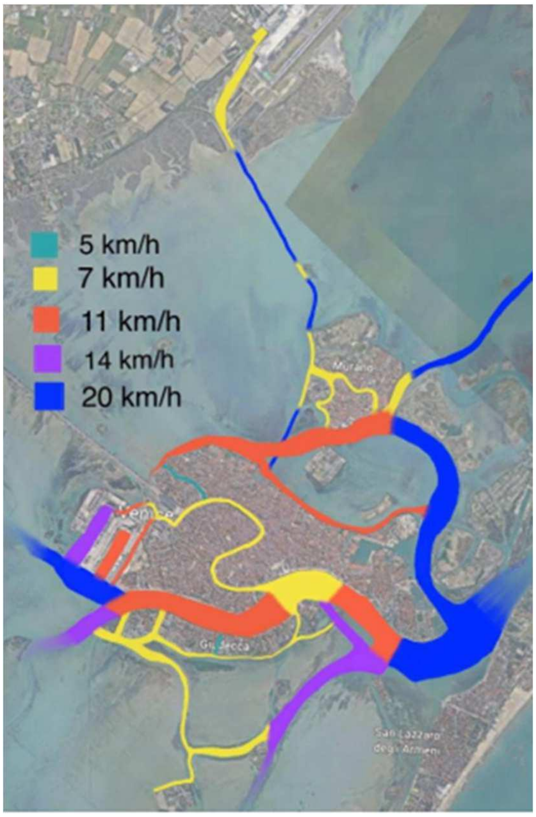

Fig. 1. Speed limits in the Venice Lagoon [2]

B. Operational Profiles

As previously discussed, the need to adhere to speed restrictions and accommodate various operational tasks of the vessel necessitates the establishment of multiple operating modes, each with a speed range spanning from 5.0 to 20.0 km/h, and different power sources. A hybrid-electric approach has emerged as the most adaptable solution to meet these design requirements. In hybrid-electric propulsion systems, the power required for both propulsion and other onboard systems can be supplied either by the Diesel engines or by the battery packs.

Considering the factors mentioned above, we can outline the following operational profiles for a hybrid-electric vessel:

a) *Navigation at cruise speed:* this condition allows the vessel to reach the cruise speed of 20.0 km/h in unrestricted waters with the diesel engines.

b) *Navigation at cruise speed with battery charge*: this condition is the same of profile a but the remaining power from Diesel engines is used to recharge the battery packs.

c) *ZEM at cruise speed*: in this condition, all the power is supplied by battery packs allowing the zero-emission navigation. In this condition the ship can reach 20 km/h and can navigate within the city center without polluting.

d) *Berthed*: it is possible to recharge the batteries and supply the onboard users by a shore connection. The available power in this profile depends on onshore infrastructure.

All the profiles are to be considered in the design process and combined with operational configuration.

III. TECHNOLOGY OVERVIEW

One of the most intriguing strategies to contain pollutant emissions involves adopting hybrid-electric propulsion systems in transportation. In recent years, extensive research and testing have been performed on vehicles and boats equipped with this technology, yielding reliable and secure outcomes. In the maritime sector, numerous cutting-edge, high-performance systems have emerged to fulfill the energy demands of hybrid-electric propulsion in both small and large vessels. Notable examples include batteries, fuel cells, and supercapacitors.

For small vessels employing hybrid-electric propulsion, batteries have emerged as the predominant energy storage solution. However, integrating these propulsion systems into small ships operating on short routes presents a formidable challenge. The vessel type necessitates maximizing passenger capacity, thereby minimizing the space allocated to energy storage and propulsion systems. The installation of energy reserves for propulsion, such as batteries, proves to be a daunting task due to the confined spaces onboard. Moreover, these vessels frequently experience abrupt speed fluctuations that place significant power demands. Additionally, there are often restrictions on the available time for recharging energy systems. To meet the substantial power requirements, it becomes imperative to accommodate a substantial number of batteries, giving rise to challenges concerning their placement and weight distribution onboard [10].

Hybrid propulsion chains generally adopt one of two primary layouts: series and parallel configurations.

A. Series Hybrid layout

In this layout, the combustion engine and the electric system are used in series [12]. The propulsion is performed by one or more electric motors connected to the propellers. The electrical power for the propulsion is generally supplied by the Energy Storage Systems (ESS), which may consist of batteries, supercapacitors, etc. This system receives energy from external sources onshore (e.g., charging columns) or from the diesel generator installed on board. One charge controller manages all the energy flows electronically (Fig. 2).

Therefore, in the series hybrid layout, the endothermic system (combustion engine – generator) and electric system (electric motors) are not mechanically connected. In particular, this configuration allows the separation of the operative points of the engine and the operative points of the propeller: only the electric motor is linked to the propeller. Therefore, such a layout can increase the global efficiency of the system by optimizing the operating point of both the combustion engine and the propeller.

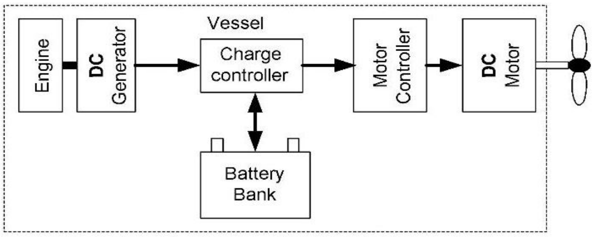

Fig. 2. Series Hybrid architecture [10]

B. Parallel Hybrid layout

This layout is characterized by the connection between the endothermic engine, the electric motor and the propeller, which are mechanically coupled with the same shaft through a gearbox and clutches (Fig. 3). Parallel hybrid propulsion systems can operate in three different profiles:

- full-electric propulsion, in which the combustion engine is disconnected by the gearbox and only the electric motor drives the propeller. The electric motor receives energy from an onboard ESS. Usually, to avoid quick battery consumption, the ship operates at low speed;
- endothermic propulsion, in which the internal combustion engine drives the propeller. The electric motor can be also dragged to recharge the ESS (e. g., the electric motor acts as a generator);
- combined propulsion, in which both the electric motor and endothermic engine simultaneously drive the propeller, allowing the ship to reach the maximum speed.

Compared with the series hybrid layout, the parallel configuration reduces the number of elements and allows the sizing optimisation of each energy source. However, it is preferred when the vessel is required to both reach high navigation speeds and guarantee short periods of full-electric navigation [13].

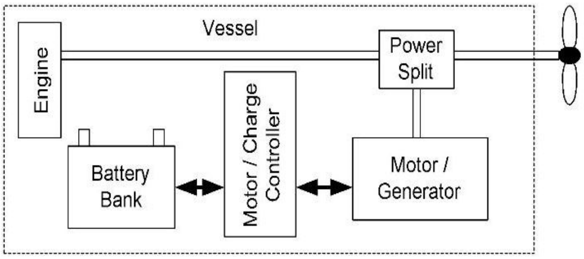

Fig. 3. Parallel Hybrid architecture [10]

IV. CASE STUDY

A completely innovative design approach was chosen: Fig. 4 displays a visual representation of the newly proposed boat. The design features a multi-hull catamaran, which represents a disruptive choice. This decision has effectively reduced wave formation during navigation, subsequently lowering the power required to operate at various speeds. Simultaneously, it has created more spacious accommodations for passengers, including those with reduced mobility.

Fig. 5 shows the general arrangement of the water bus: passengers embark via two entrances positioned in the ship's central area. The passenger cabin is located at the rear of the vessel and can accommodate 4 wheelchair users, 120 passengers inside the cabin, and an additional 30 in the aft-garden area. The maximum capacity of the main deck is 500 passengers. The wheelhouse, positioned centrally and elevated above the main deck, ensures optimal visibility.
On the deck, there is also an access hatch leading to the Diesel-generator compartment, located beneath the wheelhouse. Finally, the two electric motors and the two battery packs are situated in the two hulls: the first set at the farthest rear, and the second set forward within the two hulls, beneath the Diesel-generator compartment.

Table III consolidates the key specifications of the vessel. Thus, the new boat will always stand out as a distinctive unit dedicated to delivering safe, comfortable, and eco-friendly transportation.

Fig. 4. Design concept of the Water Bus

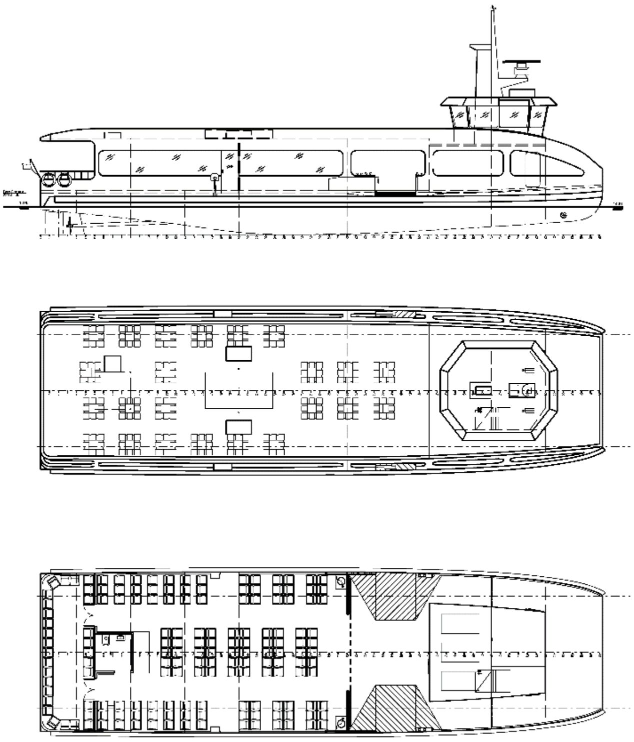

Fig. 5. General Arrangements of the Water Bus

TABLE III. MAIN CHARACTERISTICS OF THE WATER BUS

Characteristic	Symbol	Value	
Length overall	L_{OA}	28.00	m
Waterline length	L_{WL}	27.89	m
Breadth	B	8.00	m
Breadth of a single hull	B_H	2.40	m
Draught, design	T	1.40	m
Displacement, full load	Δ	98.97	t
Speed, maximum	v_{max}	20	km/h
Passengers		500	/
Crew		2	/

A. Route Analysis

Water bus operating in the Venice lagoon have a fixed operating profile that can be taken as a reference for the design of the propulsive system. Thus, in order to select the proper storage system to be installed onboard, the authors have considered a round trip route within the Venice Lagoon, involving both internal and external paths, which connects San Marco Square to Punta Sabbioni, as shown in Fig. 6.

The route consists of two sections, whose characteristics are listed in Table IV. The route has been analyzed in terms of speed limits, length, travel time, and average speed, dividing each sector into three phases:

1. Acceleration;
2. Constant speed based on the weighted average of speed limits;
3. Deceleration.

Data are shown in the Fig. 7.

Fig. 6. Route Analysis

TABLE IV. ROUTE ANALYSIS

Section	Length [km]	Travel time [h]
San Marco Sq.- Lido	2.90	00:12:00
Lido (Stop)	-	00:02:00
Lido – Punta Sabbioni	6.50	00:21:00
Tot.	**9.40**	**00:35:00**

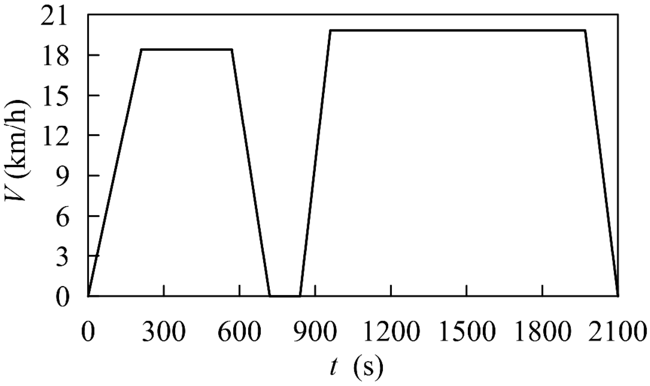

Fig. 7. Speed Analysis

B. Power prediction

Considering the speed limits in the Venice Lagoon, a round-bilge symmetric hull form has been chosen. The resistance prediction is based on the results coming from the Series '64 [14], which is a systematic series of displacing/semi-displacing catamarans (i.e., length Froude number $0.2 < Fn_L < 1.0$) having S/L larger than 0.2, where S is the distance between the centreline of the demi hulls and L is the length at the waterline. In this study, a fixed S/L ratio has been assumed. Hence, the values have been corrected to fit the actual distance between the demi-hulls (Fig. 8). The obtained brake power is provided in Fig. 9.

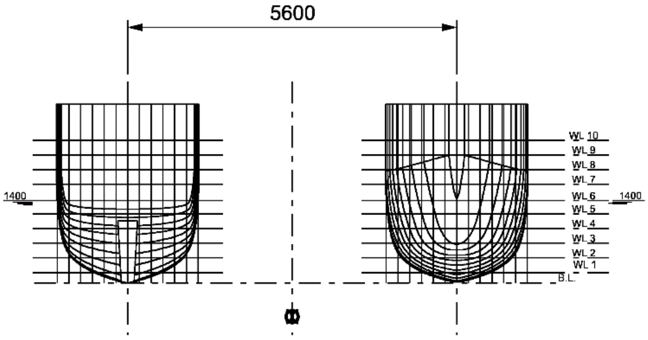

Fig. 8. Body Plan

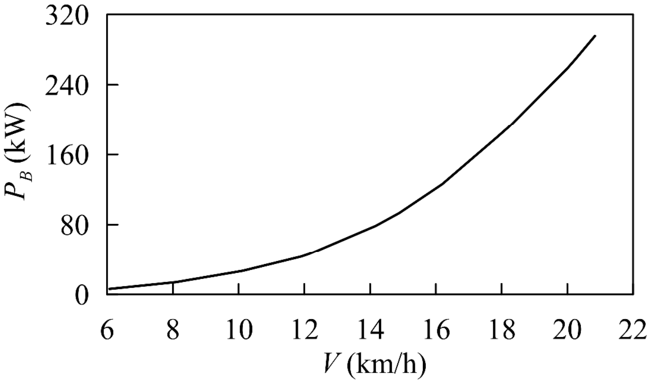

Fig. 9. Brake power prediction for the round-bilge catamaran

To draw up a reliable energy balance, an average consumption of 50 kW was assumed for the various on-board users, such as maneuvering systems, battery packs ventilation, outfitting and battery charger, navigation system, HVAC, and pumps.

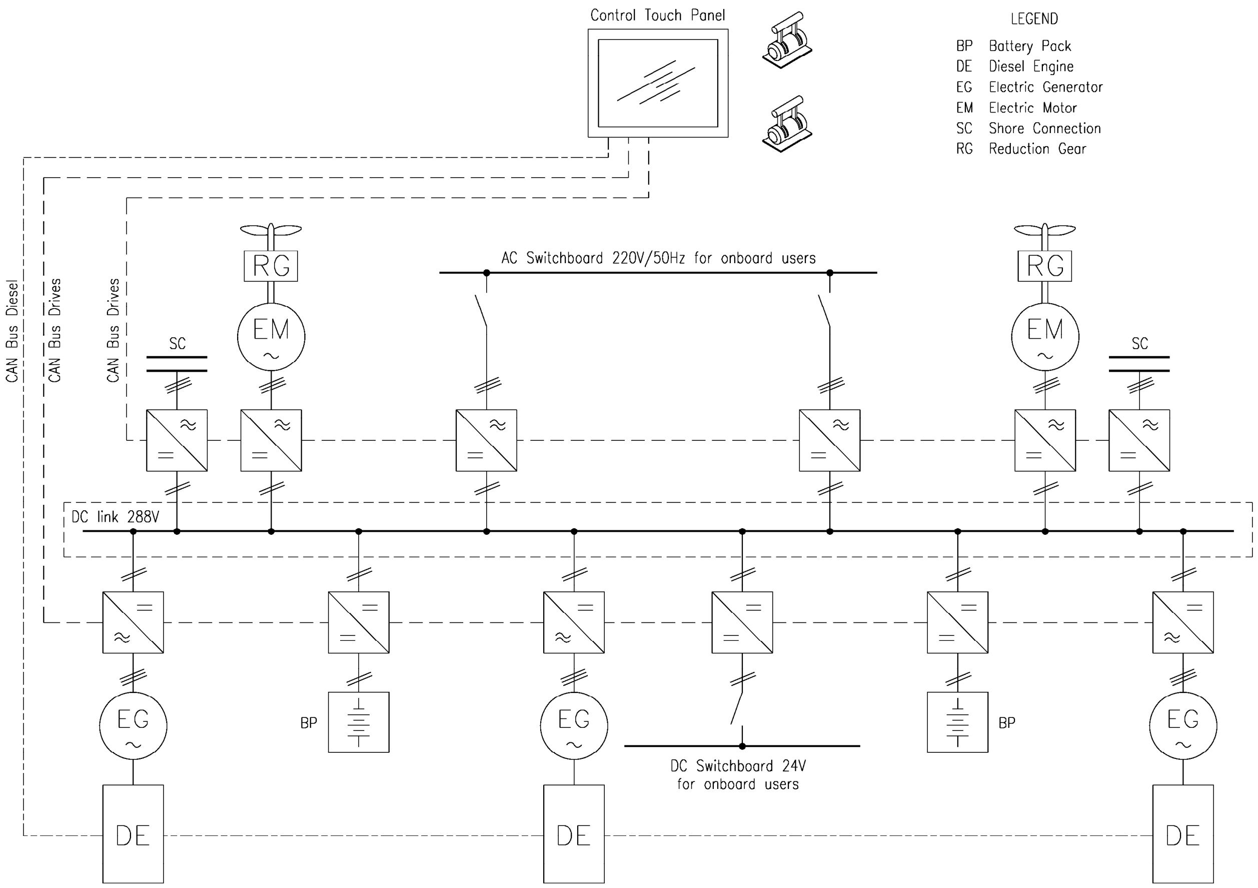

Fig. 10. Integrated LVDC Shipboard Power System

C. *Integrated Power System*

For enabling the ZEM navigation for as long as possible, the Integrated Power System (IPS) is to be conveniently designed to satisfy the energy requirement.

The IPS architecture adopted in the new water bus is shown in Fig. 6, where a Low Voltage DC (LVDC) distribution system has been arranged for the intrinsic easiness in integrating battery packs. Such a DC power distribution is commonly adopted on yacht and working-unit applications, as reported in [15].

The LVDC shipboard power system, DC bus voltage of 288 V (Fig. 10), presents the following components, which are capable of guaranteeing the aforementioned performance by exploiting the ZEM navigation:

- 3 Diesel Engines (DE) coupled with Electric Generators (EG) having a power of 130 kW at rated speed of 3000 rpm 230V 50 Hz AC;
- 3 AC/DC power converters (D) to interface the AC Diesel Generators and the LVDC bus;
- DC/AC power converters (PD) for supplying the electric propulsion motors (EM) 2 x 147 kW;
- 2 $LiFePO_4$ Battery packs, each having a capacity of 100 kWh@288V and an energy efficiency of 86,6%;
- DC/DC power converter (C) for feeding the low voltage (24 V) DC users;
- DC/AC power converters for supplying the shore connection.

Based on the design choices and considering operational profiles *b* (red line) and *c* (green line), the entire route has been divided into two segments (Fig. 11) and the energy required for the route has been calculated (Table V).

Fig. 11. Operational Profiles

Furthermore, at the end of each route, it is possible to recharge the batteries and supply the onboard users by a shore connection for 10 minute. It is scheduled using a 200 kW ground charger, resulting in an energy increase of 23 kWh for the energy storage system.

As a result, in terms of autonomy, it is possible to make 8 trips (6h of navigation) without the need to stop the ship. In the event of a complete battery discharge, about 1-hour stop is required for their recharge.

TABLE V. ENERGY BALANCE

Section		Operational Profiles				
		b (kWh)			c (kWh)	
		Prop.	Users	Battery Charge	Prop.	Users
San Marco Sq.-Lido	1	-	-	-	2.03	2.72
	2	-	-	-	20.9	5.00
	3	-	-	-	1.60	2.08
Lido	Stop	-	-	-	0.00	1.74
Lido - Punta Sabbioni	1	-	-	-	0.47	1.36
	2	84.82	13.75	3.63	-	-
	3	-	-	-	0.23	1.75
Tot.		**102.2**			**40.3**	

V. CONCLUSIONS

This study presented an investigation into the design of a catamaran as an innovative generation of water bus for everyday commuting in the Venice Lagoon, with the capability to achieve Zero Emission Mode navigation. The primary focus of the authors was on maximizing the utilization of electric propulsion powered by batteries to reduce both pollution and noise emissions. The study took into account the design constraints imposed by the unique geography of the Venice Lagoon.

The authors placed particular emphasis on examining the battery performance under various operational conditions. The batteries were found to be an ideal energy source, ensuring the boat's operational efficiency without any significant limitations. Unlike situations where using batteries as the sole energy source imposes speed restrictions to extend autonomy, the catamaran can attain high speeds without compromising its operational duration. Additionally, the onboard diesel-generators serve the dual purpose of providing emergency power for a return to port and supplying the energy required to recharge the batteries during the navigation in the unrestricted water.

In conclusion, the adoption of electric propulsion for passenger boats in the Venice Lagoon would make a significant contribution to reduce both noise pollution and environmental harm. While the Venice Lagoon represents a relatively small portion of global maritime traffic, it can serve as a catalyst for change. The overarching goal of ecological sustainability, as underscored by this study, emphasizes the importance of prioritizing the use of new technologies as vital resources for preserving the planet.

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