Electrification of Vessels for Garbage Collection and Treatment in Venice Lagoon

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***Abstract*— Nowadays, reducing pollutant emissions is of fundamental importance. In particular, in areas where urban public transport is carried out almost exclusively by boats, these represent the primary factors on which it is necessary to intervene. The conversion of current diesel units into hybrid-propelled ones is essential to preserve the marina and the environment in areas considered UNESCO heritage sites such as Venice. This document concerns the study of the first hybrid vessel built for garbage collection in the old town of Venice. Paying attention to the system engineering innovations and the results of the tests carried out on board, the authors present some considerations regarding the changes necessary to convert the current diesel propulsion into a hybrid one, with the aim to enable navigation in Zero Emission Mode.**

***Keywords*— pollutant emissions, hybrid-propelled vessels, propulsion system conversion, zero emission mode navigation, green boatbuilding**

I. Introduction

Air pollution is one of the most discussed topics worldwide. Due to the growing attention in sustainable transportation [1] and given its importance as one of the main contributors in global air pollution, water transportation has undergone a green transformation. In particular, the aim of reaching a Zero Emission Mode (ZEM) navigation as regards air pollutant emissions requires various measures [2,3]. However, without an extensive analysis that considers the advantages and disadvantages of one particular pollution reduction's technology over another, their application can be harmful (e.g., open loop scrubbers can reduce substantially atmospheric emissions of sulphur dioxide SO_2 but, on the other hand, it also creates an highly acidic discharged effluent water, with important consequences on the marine environment [4]). This analysis is particularly important in some peculiar areas around the world, where public services must also be performed by boats [5–7]. However, even among all these areas, the city of Venice represents a unique case.

Since 1987, Venice and its Lagoon have been designated by UNESCO as World Heritage Sites due their uniqueness and beauty. The Venice Lagoon, with its 550 km² of extension, is the largest Italian lagoon with typical sandbanks and shoals as well as nature reserves and fish farms. Within this area, boats are the only means of transportation available. Moreover, all the activities usually carried out by cars and trucks in other cities must be performed by vessels [8,9], with an unavoidable growth in maritime traffic. One of the most important consequences regarding the environment is the increase in air pollution and, in particular, in PM10 emissions. PM10 are inhalable particles of Particulate Matter with maximum diameters equal to 10 µm [10]. Studies carried out over the past few years in Italy showed how PM10 emissions exceeded the limit value of 50 $\mu g/m^3$ released in the atmosphere more times than the maximum allowed in a year (35 times/year, [11]). In particular, Table I shows the results collected in 2019 regarding the exceedances of daily limit value of PM10 emissions for the area of Venice [12]: as highlighted from the detectors placed inside Venice old town (Sacca Fisola and Rio Novo), PM10 emissions exceeded the limit value respectively 57 and 46 times in a year. This fact has instilled in public opinion a series of considerations regarding the beneficial impact that the implementation of reduction pollutant's measures could have for the city. Another fundamental aspect is related to the particular conformation of Venice and the surrounding Lagoon. Due to the peculiar features of these areas, navigation is strictly regulated by several public institutions such as for example Regione Veneto and Coastguards [13]. These bodies have set specific limits in terms of maximum speed permitted inside the Venice Lagoon: in particular, the range of limits goes from 5 km/h in the narrow internal canals of the city to 20 km/h in the lagoon outside, where no specific obstacles are present (Figure 1). These limitations, together with the presence of old town's narrow canals, represent the main drivers regarding vessels design designated as public services inside the city (i.e., public transportation, garbage management, first aid, public security).

Proposing innovative solutions to enable a ZEM navigation during public services execution inside Venice old town without any type of trade-offs led the authors to implement the study of a hybrid-propelled vessel aimed at collecting and treating garbage in the area. The designed unit hereby presented takes into account all the environmental, operational, and regulatory limits abovementioned and represents the prototype of a new series of innovative vessels.

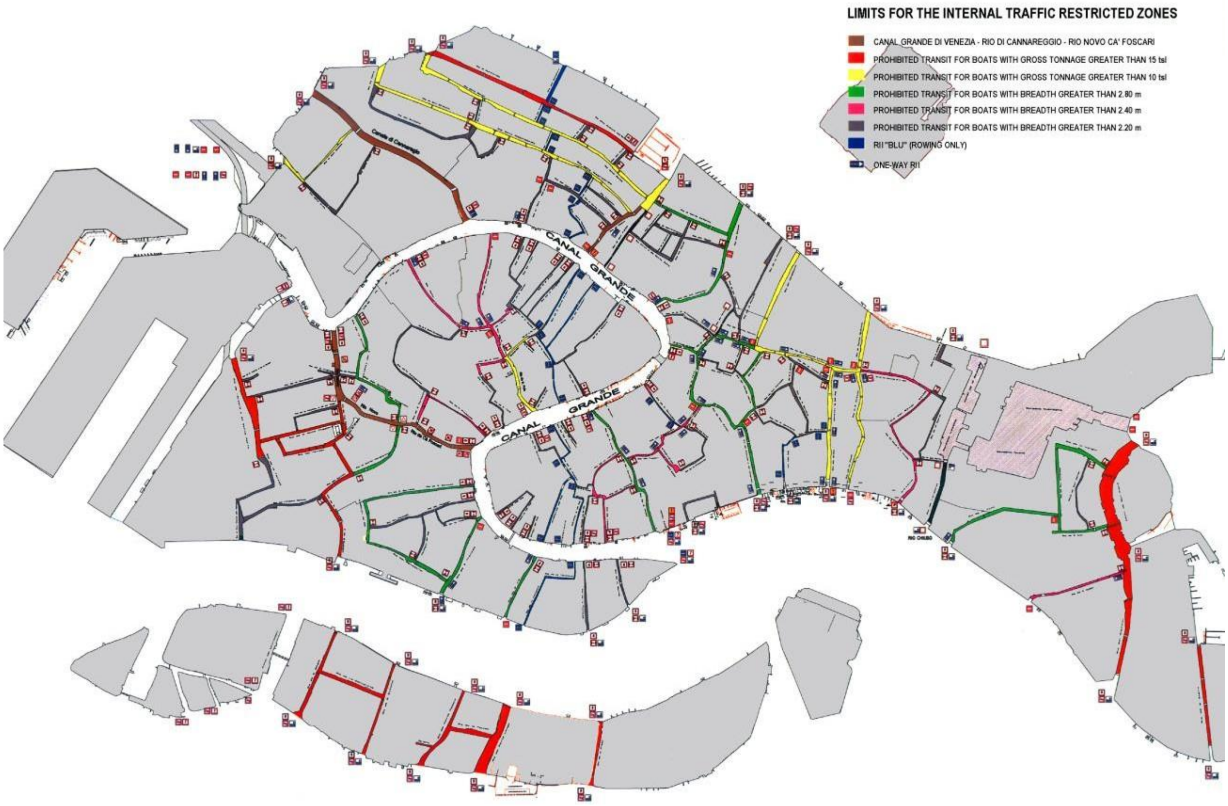

Fig. 1. Speed limits inside the Venice Lagoon

TABLE I. EXCEEDANCES OF DAILY LIMIT VALUE IN A YEAR–PM10 DETECTORS IN VENICE PROVINCE (2019)

Station	**Exceedances of daily limit value**
VE – Parco Bissuola	57
VE – Sacca Fisola	57
VE – Rio Novo	46
VE – Via Tagliamento	68
VE – Via Beccaria	68

II. VESSEL DESIGN AND CHARACTERISTICS

For all the reasons explained in the Introduction, Venice is an ideal test field for hybrid propulsion systems.

The present research aimed at assessing the performance of the first hybrid-propelled prototype designed for garbage collection and treatment in Venice, seeking the best compromise solution between efficiency and respect for the environment.

In the Venice area, garbage collection implies the following several phases: door-to-door collection, accumulation and transshipment at collection points, loading on boats set up for service, and unloading of garbage in the designated area for sorting.

As a result, a hybrid prototype of vessel (herein referred as MTR-HC that stands for "Motobarca Trattamento Rifiuti - Hybrid Compactor") was designed and built for garbage collection and treatment in Venice old town and islands by VERITAS (Veneziana Energia Risorse Idriche Territorio Ambiente Servizi), Venice's garbage management company.

The MTR-HC vessel is conceived to reach the lowest possible environmental impact, maintaining the same operational characteristics of current diesel boats. In particular, the vessel was designed in order to pursue the following targets:

- reduction of fuel consumption and use of primary energy;
- reduction of maintenance costs;
- use of green fuel;
- noise reduction;
- reduction of pollution both in terms of atmospheric emissions and probability of pollution due to oil spillage;
- increased comfort for the operator.

The vessel, characterized by one continuous deck and by a lodging hold for the garbage compactor and the crane, has an entirely grade A naval steel transverse hull, with floor plates placed every 450 mm and shell plating made up of longitudinal sheets. The General Arrangements and the main characteristics of the MTR-HC unit are reported in Figure 2 and Table 2, respectively.

To perform effectively its tasks, the vessel is armed with some important equipment such as a seawater-powered hydraulic crane, which can lift and move weights up to 200 kg, and a 11 m^3 garbage compactor. Furthermore, in order to ensure the normal operations of the vessel, it is equipped with a radar, housed in the afterpeak and liftable by a telescopic rail featuring gas pistons, and a cockpit abatement system, used to allow the vessel to navigate under the canals low bridges in every tidal conditions.

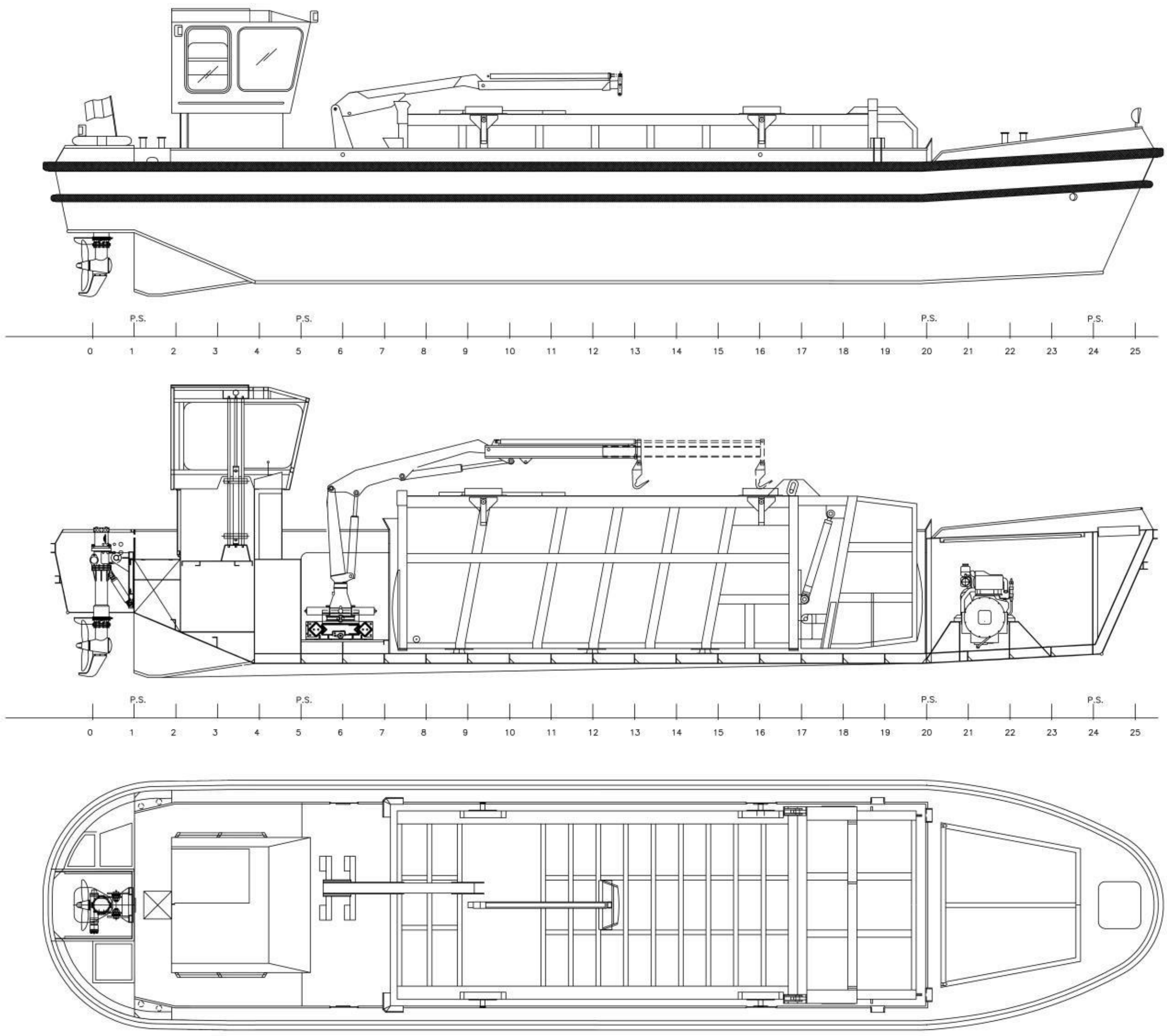

Fig. 2. General Arrangements of the MTR-HC unit

TABLE II. MAIN CHARACTERISTICS OF THE MTR-HC VESSEL

Main characteristics	
Length overall	12.09 m
Length between perpendiculars	11.20 m
Breadth	2.5 m
Depth	1.3 m
Draugth	0.8 m
Gross tonnage (Italian national)	8.75 tsl
Lightship displacement	10.78 t
Full load displacement (at departure)	21.13 t

III. HYBRID-ELECTRIC PROPULSION SYSTEM

A. *Hybrid-electric System Description*

In order to achieve all the previously set goals the vessel has been equipped with innovative and complex systems.

In particular, it is equipped with both an Electric Power System (EPS), suitably designed to satisfy all the on-board Users (U_n), and a Sea-Water Hydrodynamic open System (SWHS), aimed at cooling engines and inverter, feeding the firefighting pump, and moving the crane and the stern drive.

In order to power effectively all the U_n introduced, a Low Voltage (LV) distribution system is used. In particular, a 270 V DC bus represents the central component of the prototype's EPS, whose layout is presented in Figure 3.

The powering part is performed by a Battery Pack (BP2), which supplies a sufficient amount of energy to all the U_n. The BP2 consists in a system containing three lithium iron phosphate batteries connected in series, which provides a high level of safety, high performance, and allows great flexibility as regards both charging and discharging cycles. The batteries specification is reported in Table 3. BP2 recharge can be performed through two different methods: via a Shore Connection (SC) plug or via a Generator Set, connected through the Electric Generator (EG) to a battery charger. The EG is coupled with a conventional Diesel Engine (DE), equipped with its own starter Battery Pack (BP1) and able to deliver a power output equal to 19.4 kW. This can be used both to extend the batteries autonomy and to guarantee, in case of emergency, the continuity of service by excluding the BP2 from the propulsion chain, in order to still have the capability of returning to the base or securing the vessel.

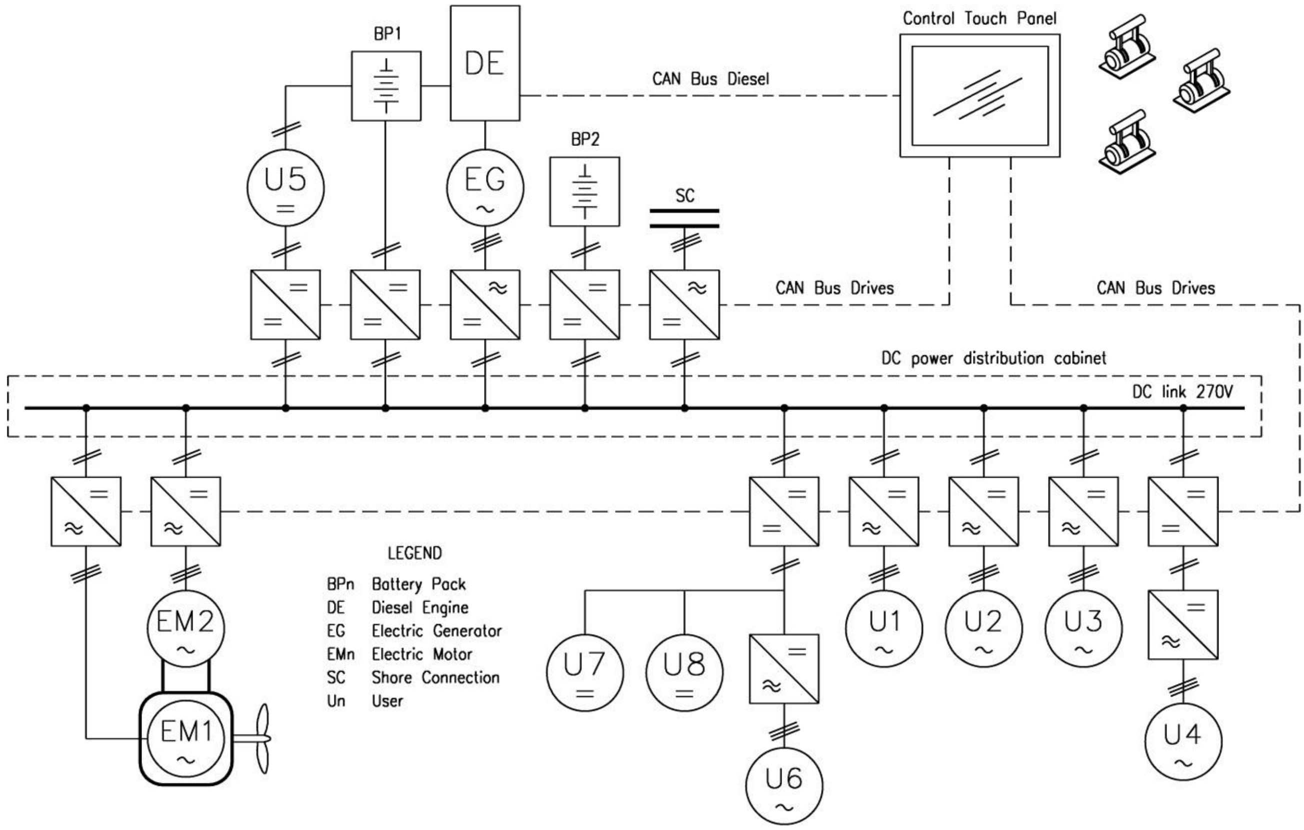

Fig. 3. Hybrid-electric system layout

The Generator Set runs at a constant speed (1500 rpm) and allows a reduction in both fuel consumption and emissions since it avoids acceleration and deceleration transients. Furthermore, the possibility of using biodiesel as fuel is another advantage.

TABLE III. BATTERIES SPECIFICATION

Dimensions (LxWxH)	1000x783x383 mm
Weight (single battery)	375 kg
Material	Stainless steel 316L
Protection class	IP65

The electric energy – mechanical work transformation, used for running the whole prototype's components, is performed by a series of permanent-magnet brushless Electric Motor (EM_n), able to ensure a higher level of reliability, low noise emissions and a lower cost compared to the traditional ones.

As a result, the U_n powered through the EPS and represented in Figure 3 are the following:

- Propeller: moved by EM1;
- Stern drive (rotation): moved by EM2;
- Crane pump U_1;
- Cockpit abatement system U_2;
- Garbage compactor U_3;
- 230 V AC equipment U_4;
- 24 V DC on-board users U_5;
- 230 V AC equipment U_6;
- Cooling water pump U_7;
- Bilge and firefighting pumps U_8.

B. Working Conditions

In order to define the energy balance (to evaluate the electrical demand of the MTR-HC prototype) two modes of operation were identified:

- Propulsion mode (P): the LV distribution system is only concerned of powering the propulsion engines, stern drive rotation and navigation systems;
- Garbage collection and treatment mode (W): the LV distribution system is only concerned of powering the crane and the garbage compactor.

1) Propulsion mode (P)

The electric power supplied by batteries at different vessel speeds is reported in Table 4 and Figure 4.

TABLE IV. ELECTRIC POWER SUPPLIED BY BATTERIES - PROPULSION

Vessel speed		**Electric power by batteries**	**Propeller speed**
[kn]	**[km/h]**	**[kW]**	**[rpm]**
0.5	1.0	1.50	300
2.7	5.0	5.60	840
5.4	10.0	32.66	1700
5.7	10.7	43.0	1900
6.2	11.5	50.4	2000

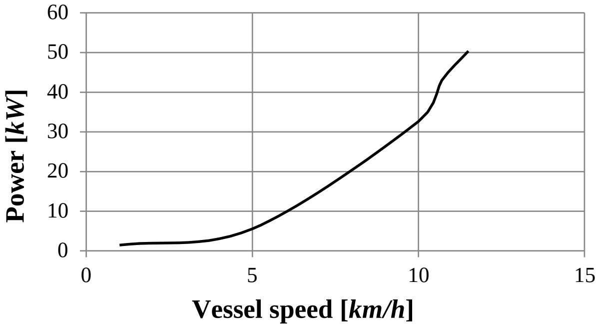

Fig. 4. Electric power supplied by batteries – vessel speed correlation

2) Garbage collection and treatment mode (W)

As far as the compactor is concerned, the values obtained showed that there is an average value of requested current equal to 20 A, with maximum peaks recorded at 100 A. These values show how the boat has a good reserve of energy to perform the requested service, compared to an available battery capacity equal to 300 Ah.

C. Energy and Power balance

Starting from these two operating modes, and by identifying which are the five most expensive routes from the electrical point of view (from garbage collection points, distributed all over Venice, to the sorting center), the total value of requested energy and the peak value of electric power were estimated. So, all the electrical equipment were properly chosen.

The five routes identified are the following: Islands of Giudecca and Murano, Castello, Cannaregio and other Islands. The most expensive route from the electric point of view is the one regarding the Giudecca Island (which requires four hours for a complete service).

Two operational profiles are expected:

- Loading phase: garbage collection is performed through the hydraulic crane, whereas the treatment is carried out by the compactor;
- Unloading phase: once the loading operation is completed, the vessel navigates to the garbage unloading point. The compactor is first lifted by an external crane, emptied out and placed back inside the vessel.

Table 5 shows the requested energy (considering the efficiency of converter, motors, and batteries) and power for each route and for each mode of operation. To consider all the equipment that are not used for garbage collection and treatment and propulsion, an entry has been added with the name Service (S) in Table 5.

TABLE V. REQUEST ENERGY AND POWER FOR EACH GARBAGE COLLECTION ROUTE

Route	Maximum energy [kWh]				Maximum Power [kW]			
	S	P	W	Tot	S	P	W	Peak
Cannaregio	2.6	33.9	13.7	50.2	5.5	50.2	50.5	56
Castello	2.8	58.8	7.4	69	6.4	52.8	49.3	59.2
Giudecca Island	3.7	38.7	9.6	52	7.1	47.2	60.4	67.5
Islands	4.5	81.3	9.4	95.2	6.6	45.7	57.7	64.3
Murano Island	3.7	77.8	12.4	93.9	6.8	51	56.6	63.4

In conclusion, it is possible to say that the system is not going to be overloaded and maximum workloads will never be exceeded; this guarantees a sufficient power to satisfy, separately, the two different working conditions of the vessel.

IV. CONCLUSIONS

This work presented a study regarding the MTR-HC ship prototype, specifically addressed to garbage collection and treatment in the Lagoon of Venice. Due to the special nature of Venice and its nearby islands, the prototype design had to observe a severe number of limitations concerning dimensions, air pollution, underwater-irradiated noise and speed limits. To be compliant with all these requirements, the prototype is equipped with two systems, a Sea-Water Hydrodynamic open System (SWHS) and an Electric Power System (EPS). The interaction between SWHS and EPS guarantees a Zero Emission Mode (ZEM) during all its working phases, a mandatory requirement inside Venice old town.

Future development will study how to reduce the global weight of the prototype (e.g., by replacing hull's steel with fiberglass or by using different Generator Set/Battery Packs) and the adoption of a Sea-Water Hydrodynamic close System, in order to reduce the SWHS maintenance (due to pump filter's occlusion).

Another path that will be studied concerns the installation on all the MTR-HC units of a hybrid module, able to grant an All Electric Mode, in replacement to the traditional diesel mode. The module will be located between the diesel engine and the pump block and it will not require any type of changes involving the hydraulic system.

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