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Collective water transport electrification: Venetian ferry boat case study

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Abstract. This paper studies and analyzes the energy transition of ferry boats used in Venice as a means of public transportation. Thus, the goal is to reduce their environmental impact by replacing the current installed thermal propulsion with an equivalent low-emission electric type. A study was conducted aimed at sizing the most suitable electric motor and battery pack to be installed, as well as the most suitable charging system for the vehicle and the area involved in this case study. The shift to electric traction will bring new challenges for the service, but also the possibility to decarbonize the water transport in Venice, preserving air quality and the monuments of the UNESCO site. Therefore, it is noted how these changes may impact service delivery.

1. Introduction

As a result of population growth and the centralization of life in large cities, mobility has become a major need to be met. Today, the transportation sector is one of the most polluting, accounting for 23% of global energy-related CO_2 emissions by sector [1,2]. In recent years, attention to the environment and emissions has increased; in fact, various authorities, such as the European Union or the COP (Conference Of Parties), have encouraged the reduction of emissions through the use of pro-collective and electric transport policies [3-6]. While the focus so far has been on land transport, in recent years several studies have been working toward the electrification of water transport [7-10]. Although most emissions come from large ships crossing oceans to transport goods, smaller vehicles crossing the lagoons of large European cities also have a significant impact [11,12]. Water pollution caused by small vessels risks damaging not only the surrounding natural environment, but also the beauty of UNESCO sites, as in the case of Venice. Following this trend, this paper aims to propose a preliminary decarbonization study applied to the lagoon public transport sector by the replacement of old ICE Vaporetti, with modern EVs and to do so, the paper is then structured as follows: Section 2 proposes a state-of-the-art analysis of the current means of public transportation in Venice, the ferry boats. Then, in order to implement a case study that makes the importance of decarbonization quantitatively understandable, a waterway crossed by these means was selected. Then, based on a physical model of the forces, the electric motor was sized with the necessary characteristics for the movement and a battery was selected to meet the service. Section 3 reports the results of the proposed case study, suggesting the motor type and battery type selected. To complete the service, possible charging stations that recharge vehicles during service or overnight are analyzed. Also, with the change of power supply, a modification of the current service, which refers only to ICE (Internal Combustion Engine) vehicles, will be appropriate. Finally, the advantages and limitations associated with electrification of lagoon mass transit are highlighted. In Section 4, the conclusions of the work are reported.

2. Case study

Venice is entirely traversed by numerous canals and, because of this very characteristic, does not allow the circulation of traditional means such as cars or buses, but only the use of boats. As a result, the city is organized with a public transportation system operated entirely by sea, with an extremely capillary apparatus that allows it to absorb the needs not only of local citizens, but also of tourists who flock to the city throughout the year. Although most greenhouse gas emissions are related to cargo ships, which make long journeys, small waterborne vehicles contribute to pollution and damage to local wildlife and beauty, as in the case of the UNESCO site of Venice. Indeed, according to a study by Ca' Foscari University of Venice, 9% of nanoparticle air pollution in Venice is generated by ships and boats [13]. Mobility management is entrusted to the company ACTV (Azienda del Consorzio Trasporti Veneziano) which manages to meet the transportation needs of more than 100 million passengers each year [14]. The fleet consists mainly of the ferry boats' characteristic, which are complemented by motorboats, motorships for transporting large masses of people, and finally ferries for transporting vehicles. A large part of ACTV's Venetian naval fleet consists of ferry boats. These have a capacity of 210 passengers and operate for 16 hours a day. They are equipped with endothermic (internal combustion) diesel-powered propulsion with a power output of 147 kW [15].

2.1. Path selection

The Venetian transportation system is divided into 22 different lines that wind through the lagoon, connecting the mainland with the various islands. In this paper, only the case of Line 1 will be analyzed, consisting of 21 stops, with the two terminuses at Piazzale Roma and Lido Santa Maria Elisabetta, shown in Figure 1.

Figure 1. Path Line 1 with the position of several stops.

The decision to conduct a study on this specific line is due to the fact that it is one of the busiest. In fact, it allows the flow of people to be channelled at the "gates" of the city to the main points of interest, whether they are tourist or business related. The time required to complete the route is about sixty minutes, including stop times. The average frequency of Vaporetto passage during the day is twelve minutes (from 6:21 a.m. to 8:21 p.m.) while it rises to twenty minutes during off-peak hours such as early morning and late evening (5:01 a.m. to 6:01 a.m. and 8:37 p.m. to 11:57 p.m.). Traffic-related regulations also exist in the marine environment to ensure the safety of users [16]. This case study is focused on one of the existing lines: the one with the highest traffic, due to utilities and touristic attractions. For the future, different case studies applied to the other lines will help the development of lagoon transport electrification.

3. Boat replacement: from ICE to Electric Vaporetto

After the selection of a representative path as case study, in this section is performed the replacement of the EV. First, the sizing of a electric motor able to satisfy the motion requirement is studied. Then the storage system for the energy required is sized in order to supply the electric motor. Once the EV is sized, further considerations can be made on the overall service.

3.1. Electric motor sizing

In the naval field, many factors must be taken into account when sizing an electric motor, among which it is of paramount importance to dwell on the friction created along the direction of motion, which affects vehicle dynamics considerably more than in conventional road vehicles. The coefficient of total resistance to motion R_{tot} of a boat is given the sum of viscous friction resistance (R_y), frictional resistance due to air (R_a) and wave resistance (R_o).

In the previous classification, the first two terms constitute the frictional resistances R_f, components related to the friction exerted by the motion of the vehicle. The latter are due to the action of force of friction that the water particles exert on the immersed surface of the hull and the action of the air particles that invest all the surfaces of the boat exposed to the outside. They can be calculated approximately with the following formula (1):

$$R_f = R_y = R_a = \frac{1}{2} \cdot C_f \cdot D \cdot V^2 \cdot S_w \tag{1}$$

Where C_f is the coefficient of friction, D is the density of the fluid [kg/m^2], V is the speed of the vessel [m/s] and S_w is the wetted surface, i.e., the surface covered by the fluid [m^2].

Finally, wave resistance R_o is that part of the aerodynamic resistance due to the occurrence of shock waves around the motion field of a moving body. Although the previous calculations were carried out, for greater resolution and completeness of the results, the characteristic curves provided by ACTV [13] were taken into consideration, which declare a total resistance (R_{tot}) value equal to 13157.89 N. From which it is possible to obtain the power value through the speed (2):

$$P = R_{tot}[\mathrm{N}] \cdot V[\mathrm{m/s}] = 73.105 \text{ kW} \tag{2}$$

The most critical case, in which the ferry boat travels at a speed of 20 km/h and the resistances are maximum, was considered for the power calculation. The above value refers to the power required by the propeller to move the ferry boat, but it does not take into account the efficiency that is useful for effective motor power sizing. Considering standard efficiency values referring to the propeller and motor of 0.7 and 0.9, respectively, yields a motor power value (P_{mot}) is equal to 116 kW.

3.2. Battery sizing

Once the motor has been sized, it is necessary to analyze the battery system to be implemented for the ferry boat for proper operation. The capacity of the batteries is strictly influenced by the applications; however, their efficiency is very high, hovering around 90%. Table 1 shows the main technical parameters of the batteries used. Assuming a nominal battery pack voltage of 550 V, the necessary number of cells to be connected in series can be found through (4):

$$N = \frac{550\ V}{V_{ch}} = 37.7 \cong 38 \tag{4}$$

Table 1. Technical parameters of the battery.

Parameter	Characteristics
Voltage (V_0)	12.8 V
Nominal capacity	138 Ah
Weight	19.5 kg
Dimensions	306 mm x 172 mm x 225 mm
Standard discharge	V_d :10 V – I_d: 150 A
Standard charge	V_{ch}: 14.6 V – I_{ch} 70 A
Internal resistance	5 mΩ

Considering a use time of the vehicle of 3 hours (h), the auxiliary services (P_{aux}) installed on board with an estimated power of 30 kW and a reserve margin imposed by law equal to 30% of the total capacity, the capacity of the battery pack (C_{bat}) equal to (5):

$$C_{bat} = P_{tot} \cdot h + P_{aux} \cdot h + 0.3 \cdot (P_{tot} \cdot h + P_{aux} \cdot h) = 569.4 \text{ kWh} \tag{5}$$

It is possible to obtain the capacity of a single module starting from the number of cells used (6):

$$C_{module} = N \cdot C_n = 5244 \text{ Ah} = 67.123 \text{ kWh} \tag{6}$$

From this calculation it is possible to obtain the number of modules (M_{tot}) needed (7):

$$M_{tot} = \frac{C_{bat}}{C_{module}} = 8.48 \cong 9 \tag{7}$$

Obtaining a total number of cells equal to 342, given by the product between number of modules (M_{tot}) and number of cells in series (N). The overall dimensions and relative weight of the battery pack are obtained starting from the nominal characteristics of the single cell, (8):

$$\begin{gathered} V_{module} = 0.306 \cdot 0.172 \cdot 0.225 \text{ m}^3 \cdot N = 0.45 \text{ m}^3 \\ V_{tot} = V_{module} \cdot M_{tot} = 4.05 \text{ m}^3 \\ W_{tot} = 19.5 \text{ kg} \cdot N \cdot M_{tot} = 6.7 \text{ t} \end{gathered} \tag{8}$$

Regarding the arrangement of the batteries inside the boat, it was planned to install them in the hull where they will be distributed to fill as large an area as possible to maximize the distribution of the weight itself.

4. Service and infrastructure renovation for the new fleet

After performing the physical model analysis and examining the resistances and forces involved, the motor can be selected. Based on the requirements considered, the motor selected for the vehicle is an induction motor. Considering the required characteristics, the sized motor will have the characteristics shown in Table 2 [17].

A similar study to that done for the motor was also carried out for the batteries. From the analysis, it was possible to select the most suitable Lithium-ion batteries for the present case study. A more dynamic and planned recharging phase than the current one will also be implemented; in fact, even considering high-power recharges, the stops of the electric vehicle will be longer than those of the ICE vehicle, and this will surely result in a revision of the current service. For the implementation of accurate charging phase, the existing depots were used: one located in the Tronchetto area and the other in the S. Elena area, as shown in Figure 1. A 150 kW power charging model is used in the two depots in order to provide DC power to the ferry boat and charge them while maintaining comparable service to the existing one [18].

Table 2. Motor characteristics.

Quantity	Characteristics
Peak Power [kW_P]	147
Continuous Power [kW]	85
Cruising speed [m/s]	5
Size [mm]	889x478x489
Weight [tons]	0.336

Currently, the busiest line has a 12-minute cadence and requires 10 ferries in both directions, 5 outward and 5 return. With the introduction of electric ferries and due to the size of the battery, each vehicle is able to make 1 round trip. After these, recharging is provided. It should also be considered that despite the elimination of the internal combustion engine, the addition of a battery pack of the resulting weight makes it necessary to reduce the number of passengers on board, from 210 to 150. Therefore, in order to keep the number of passengers carried constant, it would be desirable to change from 10 operating ferry boats to 12, decreasing the travel time between two boats. In addition to this knowledge of the service, it is necessary to remember that the charging time of a ferry boat is 120 minutes. Mixing the needs of the service with those of charging, it is easy to see that the number of electric vehicles needed to meet the service will be 24. In addition, modification of depots is needed to install 12 infrastructures that can function to recharge vehicles while they are not running. In addition, the electric motor has a simpler structure, which reduces the response time in case of failure. At the same time, vibration from the ICE is avoided. Finally, it should be remembered that ferry boat service requires a non-constant speed, for which the electric motor is more suitable, maximizing motor efficiency, unlike the ICE. On the other hand, the electrification of these vehicles has disadvantages that limit their use. The first is the limited range: in order to achieve an acceptable range for the service, a large battery pack had to be fitted, which increased the weight of the vehicle and limited the number of passengers. As can be deduced from the results reported, at the moment, to replace ICE Vaporetti with electric Vaporetti, an increase in the fleet is necessary, due to the recharging times of the vehicles on the route. This is also due to the fact that inserting numerous high-power opportunity charges could create imbalances in the electricity grid. However, with the necessity of the decarbonisation of the mobility sector also in lagoon transport, this case study represents one of the possible scenarios for the electrification of the service.

5. Conclusions

Based on the environmental goals set by the authorities, the importance of decarbonizing the transportation sector is outlined. While many types of land transportation are electrifiable today, the same is not true for water transportation. Therefore, in this paper the decarbonization of a collective water transport in one of the most important cities in Italy, Venice, is implemented. Following a force-based model, we evaluate what type of electric motor and battery can be used in order to switch from an ICE ferry to a fully electric one, also highlighting how the transportation service can change to meet the same demand. However, several complications remain that limit its development. In the future, with better performing batteries and a more resilient network, the electrification of these vehicles will receive an even greater boost.

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