A simulation model for hybrid-electric inland waterway passenger vessels

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Abstract. The increasing focus on air pollution reduction for transportation systems requires to adopt new technologies and innovative solutions to limit vehicles emissions. In case of inland waterway transportation (IWT), once vessels have to operate close to urban areas or in natural reserves, the necessity to provide a 'green navigation' is of primary importance. With this specific aim, especially for small crafts, the adoption of an hybrid-electric power system grant a significant pollution reduction, leading also to a possible Zero Emission Mode (ZEM) navigation. However, the particular configuration of inland waterways makes the estimation of vessels' hydrodynamic performances harder compared to a seagoing ship, because of restricted waters effects, affecting both resistance and manoeuvring characteristics. For this purpose, time domain simulation program has been developed to estimate the effective power demand of an inland vessel during a specific route. The program has been tested on the specific case of a passenger vessel designed for the Grado lagoon, where all the reference route bathymetric data were available. By means of the simulations it has been possible to state whether the vessel is suitable to operate in ZEM mode during the service.

Keywords. Inland navigation, sustainable mobility, hybrid-electric craft, manoeuvring simulation

1. Introduction

The design of modern and innovative passenger vessels for inland navigation, requires nowadays the adoption of technologies oriented to reduce pollutant agents in the atmosphere[1]. In fact, the modern regulations requires more stringent constraints to the engine emission, especially once the vessel should operate in natural reserve areas or in proximity of urban zones.
Then a solution oriented to hybrid-electric propulsion[2] is a suitable way to limit emissions up to totally extinguish them. In such a case the so called Zero Emission Mode (ZEM) navigation can be ensured[3], leading to a sustainable project, especially for passenger transport inside urban or environmental protected areas[4].
However, to ensure that a new craft will be able to grant ZEM navigation on a certain route, it is essential to determine the total power demand needed for the travel, considering all the systems installed on board, the speed limitations and the peculiarities of the

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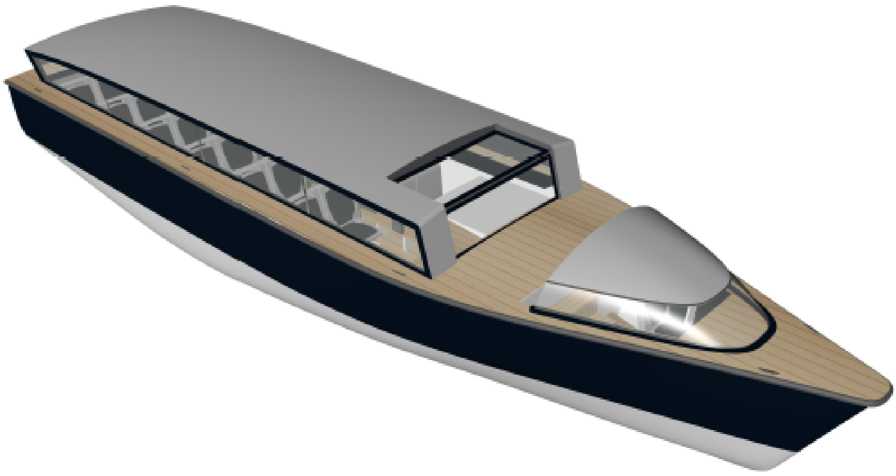

Figure 1. 3D-view of the vessel under investigation.

specific environment. In case of a navigation inside lagoons, the complications rise up, since the vessel should operate in restricted waters[5], being subjected to shallow water effects on resistance, propulsion and manoeuvring. In fact, a conventional route for passenger transport is done within channel subjected to different seabed conditions and speed limits, leading to transition in different hydrodynamic regimes.
Through this paper a route simulation model has been implemented for a new designed passenger craft for the Grado lagoon, provided with an hybrid-electric propulsive system and propelled with two electric pods. The main service routes of the vessel have been simulated in such a way to accurately determine the power demand needed for propulsion, granting an accurate input for the battery system design, which is essential to ensure ZEM navigation.

2. The passenger craft

The present study will be carried out on a 11 meters inland-water vessel (Figure 1), designed to perform passenger transport duties inside the Grado lagoon.
The environmental characteristics of the operative scenario involve the necessity to sail in shallow water and restricted channels, leading to hull forms with shallow draught. However, the vessel under analysis was originally designed to sail both in shallow that in unrestricted waters, reaching a maximum sustainable speed above 10 knots, means that the hull form is a compromise between the two different duties. Taking a look to the body plan in Figure 2, it is possible to see how the combination of an operative profile oriented to sail around Fn of about 0.50, means along the peak of wave resistance coefficient, and another one oriented to shallow water, led to a hull form with a narrow waterline entrance angle and waterlines shaped for minimise wave making resistance, combined with a small draught to avoid groundings.
The resulting hull form got also a transom area dimensioned to face the higher speeds,

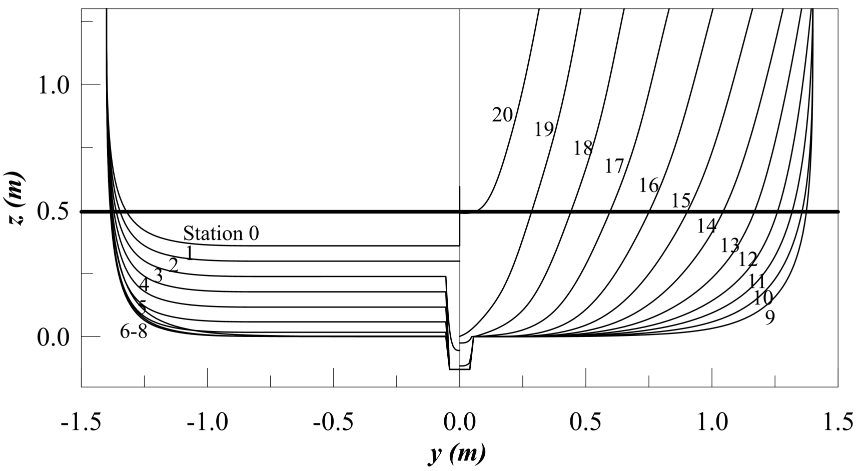

Figure 2. Body plan of the designed vessel.

Table 1. General particulars of the analysed passenger craft.

Length between perpendiculars	L_{BP}	10.000	m
Length at design waterline	L_{WL}	10.504	m
Length overall submerged	L_{OS}	10.504	m
Breadth	B	2.769	m
Design draught	T	0.495	m
Volume	∇	9.2	m^3
Wetted surface	S	34.6	m^3
Bare hull wetted surface	S_0	31.6	m^2
Appendages wetted surface	S_{APP}	3.0	m^2
Longitudinal centre of buoyancy	LCB	-5.184	$\%L_{BP}$
Longitudinal centre of floatation	LCF	-4.452	$\%L_{BP}$
Block coefficient	C_B	0.602	-
Midship coefficient	C_M	0.867	-
Prismatic coefficient	C_P	0.695	-

means the solution is not ideal for sailing at low speed in shallow water. In any case, the fact that the vessel should respect two different and antithetic requests, led to a compromise solution, that in any case will not affect to much the performances in both operative ranges. In Table 1 it is also possible to see an overview of the hydrostatic characteristics of the vessel, highlighting another time the peculiarities typical of a vessel designed for a relatively high speed in displacing regime, especially considering *LCB* position.
It is interesting to observe the relative low draught resulting from the hull modelling, this is essential to avoid groundings and minimise the possibility to sail along critical regimes conditions in channels navigation. It must be noted that, even tough in Table 1 a reference draught of 0.495 metres is indicated, the effective minimum z of the vessel refers to a drought of 0.680 metres due to the presence of the central keel. The referenced design draught T is reported with the value used to determine geometric hull coefficients.
The propulsion system mounted on board is composed by two electric steerable pods, each one mounting a fixed pitch three-bladed propeller having a diameter D of 0.400 m,

a pitch-diameter ratio P/D of 1.008 and an expanded-disk area ratio A_E/A_0 of 0.578. As it will described in the next section, particular attention should be given to the modelling of the pod system, in order to simulate in a correct way the thrust and power demand during transfer.

To have a relevant *green* profile on the vessel, a full electric solution has been developed for the propulsion system. This is resulting in having an Integrated Power System (IPS) designed to satisfy preliminary pre-determined energy requirements, involving all the auxiliaries installed on board, means: manoeuvring system, engine room ventilation, outfitting, battery charger and propulsion.

In a preliminary evaluation, once the vessel is sailing on a pre-determined course, the above mentioned electrical loads can be assumed as constant through the entire course. In such a case, considering that during transfer it is supposed to travel without battery charging, the manoeuvring loads are supposed to be around 0.5 kW, the ventilation services 0.3 kW, while propulsive loads are speed dependent, being about 1 kW at 3 knots and 7 kW at 6 knots in deep water.

With the above considerations, the IPS chosen for the considered vessel is composed by a Low Voltage DC (LVDC) distribution system, selected for the intrinsic easiness of battery pack integration[6]. The LCDV on-board system, using a DC bus voltage of 48 V, is composed by the following subsystems:

- *Diesel Generator* having a power of about 16 kW.
- *AC/DC power converter* to interface the Diesel Generator with LVDC bus.
- 2 *battery packs* connected in series in order to provide 1124 Ah and 53.95 kWh (however to avoid a discharge above 50%, a capacity of 26.97 kWh has been considered for standard duty).
- *Primary battery charger* to restore the battery's energy reserve by means of an AC plug-in shore connection.
- *Secondary battery charger* to recharge the battery buffer from DC bus when the Diesel Generator is running.
- 2 *DC/AC power converters* to supply the electric propulsion motors (12 kW each) of the steerable pods.
- 2 *DC/AC power converters* to supply the electric motors for the pods' steering system.
- *DC/DC power converter* for feeding the low voltage (24 V) DC users.
- 2 *contactors* to configure the IPS.

In particular, the designed IPS should be managed by means of coordinated action of the contactors, in such a way to ensure the different navigation profiles the vessel will face. As already mentioned, the IPS system has not been implemented in the time domain simulation program, where particular attention has been given to the manoeuvring and propulsion system.

3. Manoeuvring model

To perform the simulation it is of primary importance to accurately model the environmental circumstances that will arise during the vessel navigation. For such a reason, the behaviour of the vessel should be described not only when the ship is sailing in standard

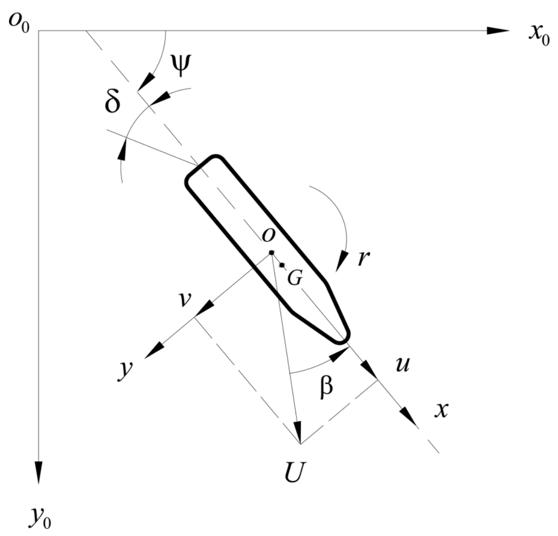

Figure 3. Ship fixed reference system adopted in the manoeuvring model.

ahead condition, but also when the vessel is keeping a certain predetermined course. That means the three degrees of freedom (3DOF) dynamics of the vessel should be described. The following model[7] has been selected to describe the vessel motion in the horizontal plane according to the ship fixed reference system of Figure 3:

$$\begin{aligned}(m+m_{uu})\,\dot{u} &= m\,r\,v + X_{TOT}\\ (m+m_{vv})\,\dot{v} + m_{vr}\dot{r} &= -m\,r\,u + Y_{TOT}\\ m_{rv}\dot{v} + (I_z+m_{rr})\,\dot{r} &= N_{TOT}\end{aligned} \tag{1}$$

where the total forces are defined with reference to the centre of gravity G.
In the traditional manoeuvring approach, the total forces X_{TOT}, Y_{TOT} and moment N_{TOT} are divided into different components: *hull*, *propeller* and *rudder* forces, resulting in the following set of equations:

$$\begin{aligned}X_{TOT} &= X_H + X_P + X_R\\ Y_{TOT} &= Y_H + Y_R\\ N_{TOT} &= N_H + N_R\end{aligned} \tag{2}$$

where $_H$, $_P$ and $_R$ denotes hull, propeller and rudder respectively.
Because the vessel under analysis is equipped with azimuthal pods, the contributions of propeller and rudder can be considered in a combined thruster force, changing motion equations 1 in the following form:

$$\begin{aligned}(m+m_{uu})\,\dot{u} &= m\,r\,v + X_H + X_{THR}\\ (m+m_{vv})\,\dot{v} + m_{vr}\dot{r} &= -m\,r\,u + Y_H + Y_{THR}\\ m_{rv}\dot{v} + (I_z+m_{rr})\,\dot{r} &= N_H + N_{THR}\end{aligned} \tag{3}$$

then adopting an adequate modelling technique for the pod, based on a B-series propeller[8] corrected to simulate the presence of the thruster housing, it is possible to easily simulate the propulsive drive.

Regarding the hull forces simulation, use has been made of the non-linear motion derivatives derived by Kijima[9], suitable for both deep water and shallow water cases. However, to ensure more flexibility to the simulation program, use can also be made of user-defined hull forces derived from measurements or CFD calculations and converted in derivatives according to cross-flow drag method[10]. The straight ahead resistance curve of the vessel must be also given as input as well as the non-linear derivatives. For the specific case, a statistical resistance has been estimated and corrected according to slender body assumption, which can be considered a suitable accurate solution for the analysed hull typology. As mentioned the vessel should operate in restricted water, so the resistance curve is corrected according to Karpov method[11] and also by channel wall effect according to[12]. In such a way the model is suitable to simulate vessel behaviour in a generic shallow or deep water environment, considering also channels wall effects.

The steering system is also simulated, allowing the vessel to follow a predetermined route assigned by means of an adequate number of way-points. At the reaching of each way-point, the auto pilot is evaluating the required heading and speed to reach the following way-point, and transmit the signals to the steering system and propulsive drive. The steering controller and propeller revolutions controllers are simulated by means of PID controller types[13].

The control is done on the base of the instantaneous error e, determined by the difference between required values and actual values at each time step. Then the correction Δx is given by the following formulation:

$$\Delta x = K_p(e) + K_d(\dot{e}) + K_i \int_0^T e(t)dt \quad (4)$$

where K_p, K_d and K_i are the constants being proportional, derivative and integral of error e respectively. That means the control system depends from the choice of the above three mentioned constants. For the case under analysis, several tests have been carried out, selecting a set of coefficients suitable to reproduce the effective steering device mounted on board an drive system.

With such a kind of components implemented on the simulation program it is then possible to proceed with course simulations.

4. Route simulations

The above described simulation model has been tested on the passenger craft on two predefined routes, significant for the vessel duty as passenger transport craft.

In order to accurately simulate the predefined routes, a set of way-points has been determined for both the selected routes, in such a way to establish also an accurate bathymetry and the channel breadth, in such a way to be able to reproduce restricted water environment. Also really important is to establish the speed limitations inside the channels, in order to respect regulations and establish a correct velocity profile essential to determine the effective power demand of the vessel during the route and determine the energy needed for the propulsive issues.

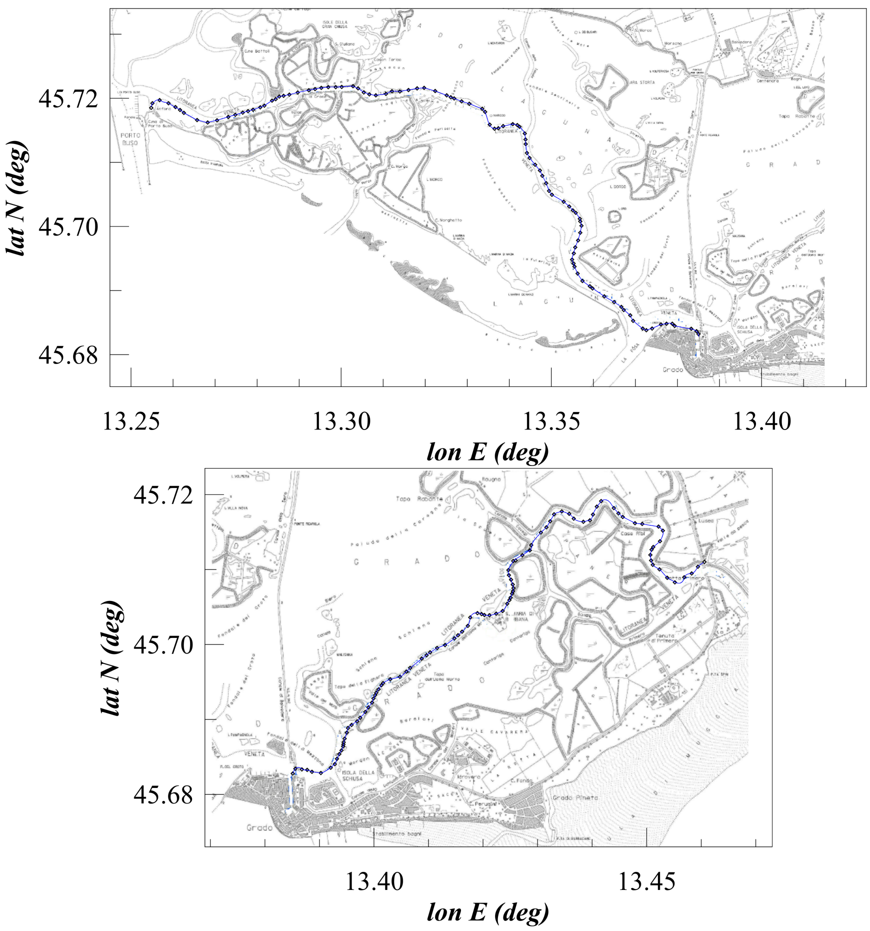

Figure 4. Grado-Porto Buso (*top*) and Grado-Primero (*bottom*) route with related way-points

The two selected routes are representative of two different travel profiles inside the lagoon. The first one (Grado-Porto Buso) is the longest route inside the lagoon (about 13133 metres), characterised by a starting phase in a large channel where speed up to 6 knots can be reached and a second tract where the channel breadth decreases and where speed limitations are allowing a maximum speed of about 3 knots. It can be stated that the route is quite regular for manoeuvring issues.

The second route (Grado-Primero) starts also in a large channel where 6 knots of speeds can be reached, but has a central part characterised by narrow and tortuous channels where speed should be reduced to 3 knots and the vessel will manoeuvre constantly to keep the course. The last part is another time in a large channel, so less problematic of the central part of the route. In its totality the route is shorter than the previous one (9449 metres), but presents for sure more critical points.

In Figure 4 the two routes are visible together with the way-points used by the auto-pilot to define the course. During the simulation the main parameters related to vessel translation, forces, power and environmental condition have been recording, leading to the collection of a really huge amount of data. For simplicity, only a few couple of signif-

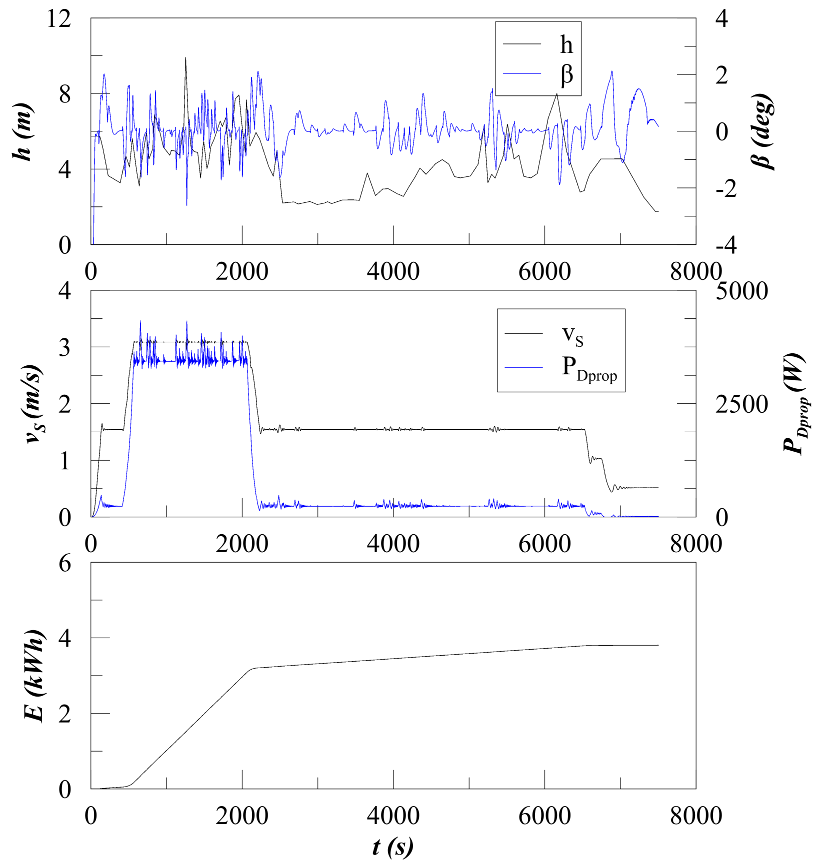

Figure 5. Simulation data for the Grado-Porto Buso course.

icant data have been reported in graphical forms in Figure 5 and 6 for the Grado-Porto Buso and Grado-Primero routes respectively. In particular a record of the water depth h is present to show the bathymetry, the drift angle β to show when the vessel is manoeuvring, the vessel speed v_s and the absorbed power of each propeller P_D. From integration of the P_D curve it is then possible to evaluate the energy needed during the travel. For this specific quantity, the first route presents an energy demand of about 4 kWh having accomplished the course in about 2 hours and 5 minutes, while the second one of about 2.6 kWh covering the selected distance in 1 hour and a half.

Then, considering the battery package installed on board, it is possible to asses that the vessel will be able to perform the first route for about 5 cycles per day (with an autonomy of more than 65 kilometres) and the second one for 7 (about 90 kilometres) without need of battery recharge. Besides it is also evident that the vessel will not need to run the Diesel Generator mounted on board to perform battery charge during travel, leading the charging process to the on-shore plug-in columns only. On the bases of this achievement, it is then clear that the proposed craft is able to perform a ZEM navigation through the whole possible operative routes and profiles inside the Grado lagoon, limiting also a lot the process of battery recharging during the shore stationing between travels.

This operative profile is also advantageous for maximise the battery life. In fact, it has

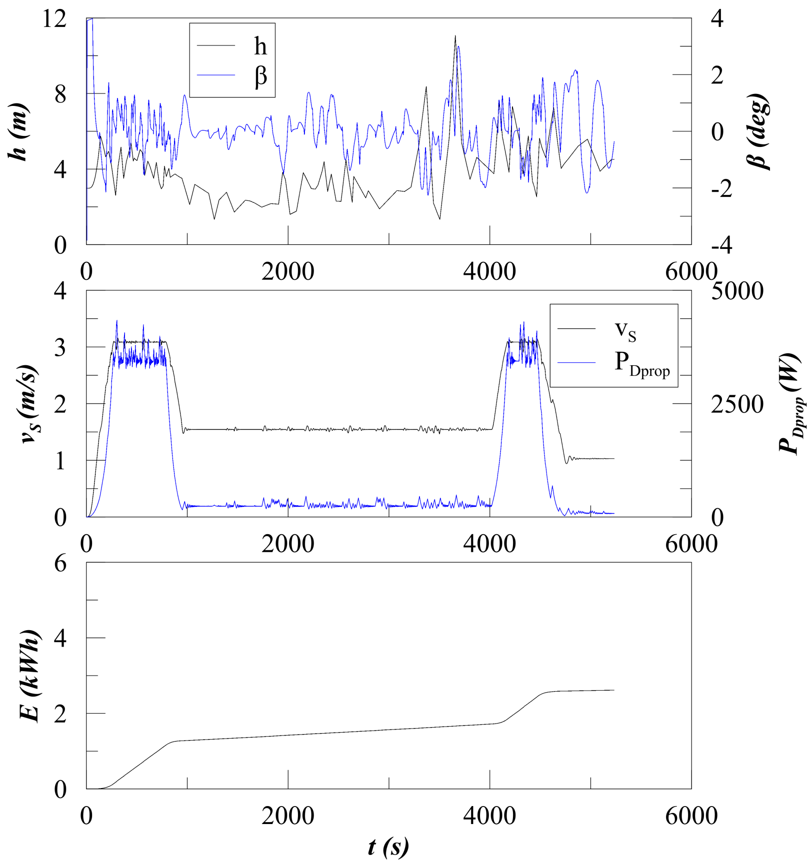

Figure 6. Simulation data for the Grado-Primero course.

been evaluated, according to supplier recommendations and considering 5 months of work per year, that the batteries will be efficient for 9.5 years.

5. Conclusions

A computational model has been implemented to simulate the specific routes of a passenger craft designed for passenger transport service inside the Grado lagoon. The typical environmental characteristics of the routes have been simulated, considering the effective water depths and channel breadths along the selected courses between Grado and Porto Buso and between Grado and Primero.

The possibility to evaluate the effective manoeuvres that the vessel will face during transfer phase allows to predict the total amount of power necessary for propulsion and consequently the total energy needed for the operation in each analysed condition. The simulations also highlights that the reduced draught of the vessel is really indicated for the selected environment, avoiding to sail in critical conditions, despite really few transitory phases that are not affecting the total power amount needed for propulsion. Besides, the simulation outcomes show that the vessel, with the battery pack currently installed on

board will be able to cover more than the required course in fully ZEM mode, ensuring the greenness of the design craft.
The current study will be a good starting point for a further improvement of the simulation platform, involving also the time simulation of the on-board electrical system, studying then the full energy profile of the vessel. By doing that, it will be possible also to perform an optimisation of the hybrid-electric system that can be mounted on-board of new units.

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