Modeling and simulation of electric system for small vessels with renewable energy integration

DOI: 10.25043/19098642.284

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Abstract

This paper presents a comprehensive analysis of the design and simulation of an integrated electric propulsion system for small boats, with the purpose of optimizing river transport from an environmental and energy perspective. The research proposes a propulsion system that combines an electric motor, a lithium-ion battery-based storage system and a three-phase charger designed for in-port recharging processes. The system components were modeled and simulated using Matlab/Simulink, incorporating real operational data and navigation profiles adapted to typical Colombian river conditions, specifically in the Atrato River. The vessel operating profiles were defined in three main modes: maneuvering (5 knots), economic (12 knots) and maximum speed (27 knots). For each mode, critical variables such as required power, energy autonomy and the frequency of recharges needed on the river route were simulated. The results indicate that operating at low speeds maximizes energy autonomy, reduces the number of refueling stops and allows for a shorter cumulative operating time, thus enhancing higher energy efficiency compared to higher speeds. The article highlights the importance of simulation in the preliminary design of electric propulsion systems facilitating the optimization of configurations and parameter tuning prior to implementation.

Key words: Electric Propulsion Systems, Modeling and Simulation, Energy Management, Sustainable Transportation, Lithium-Ion Batteries, Vessel, renewable energy, integration

How to cite this article
To cite this article, use the following format:

IEE Format
[1] J. D. López Suarez, J. P. Villegas Ceballos, D. Gonzalez Montoya, C. Escudero Quintero and E. Gi. Paipa Sanabria, "Modeling and simulation of electric system for small vessels with renewable energy integration" Ship Science and Technology (Cartagena), vol. 19, no. 38, pp. 7-16, 2026. DOI: 10.25043/19098642.284

Date Received: August 10th, 2024
Date Accepted: November 17th, 2024
Publication Date: February 9th, 2026

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Introduction

As part of the global energy transition, the inland waterway transport industry faces major challenges related to fleet modernization, environmental sustainability, and improvements in operational efficiency. In Colombia, where rivers are the main lifeline for transporting goods and people in remote areas, the adoption of electric mobility technology represents a strategic opportunity to reduce the environmental impact and improve the quality of life in riverside communities. However, the national inland waterway sector is constrained by deficient infrastructure and a historical dependence on internal combustion engines, which generate significant pollutant emissions and high operating costs [1].

In Colombia, passenger and freight transport is essential for communities that lack access to road infrastructure and rely on rivers or the sea as the only entry route. The country is also developing in the tourism and fishing sectors, which depend mainly on vessels powered by internal combustion engines. For this reason, efforts are directed towards encouraging the adoption of electric motors, which, unlike fossil fuel-based engines, emit less CO_2 and are more efficient.

The concept of electromobility—defined as the use of an electric propulsion system onboard a vessel—aligns with global initiatives to promote the decarbonization of transportation. Technologies such as electric motors, lithium-ion batteries, and hybrid systems integrating renewable energies provide innovative solutions that can transform the inland waterway industry into a model of sustainability and efficiency.

This article focuses on the modeling and simulation of electric systems for small vessels [2], [3] (Ascencio Medina et al., 2019; Shahira et al., 2022), integrating renewable energy technologies to enhance performance and reduce environmental impact. Through a simulation-based approach, the objective is to deploy a propulsion system composed of an electric motor, an energy storage system, and a port charging system, thus adapting energy technology to the specific needs of inland waterway transportation [4], [5], [6].

When deploying a vessel, it is crucial to define its specific application, whether for food transportation, recreational boats, or ferries operating on short distances, due to the cost and complexity of implementing current electric systems. For this reason, the initial proposal is to implement systems digitally using development software that includes components related to vessels, energy generation, and energy storage. In this context, Matlab/Simulink is presented as a widely used tool offering a broad range of components specifically designed for the simulation of transport and energy systems.

The objectives of this study include the development of a simulation model that allows for the evaluation of vessel performance under real operating conditions. Subsequently, the analysis focuses on energy management and vessel autonomy, ensuring efficiency and sustainability requirements are met on selected inland routes. The approach taken in this work is grounded in the emulation of a propulsion system through Simulink simulations, where vessel components are modeled based on real parameters. Considerations such as the motor's speed-power curve, the state of charge of the batteries, and the vessel's operational modes were taken into account, enabling a precise and comprehensive representation of the system.

The remainder of this article is organized as follows: Section 2 presents the design of the propulsion system and its components; Section 3 details the energy storage system and the port recharging process; Section 4 addresses the emulation of the vessel's operating profile; and Section 5 concludes with findings and recommendations for future research.

Emulation Methodology

For the emulation of the proposed vessel, renewable technologies were employed, and the vessel's performance was evaluated in a local context by replicating operating conditions. The objective of this work is to implement a propulsion system through simulation, which includes an electric motor, an energy storage system, and a port recharging system. The aim is to adapt electric energy technologies to vessels to reduce environmental impact and improve efficiency in inland waterway passenger and freight transport.

The proposed simulation provides a foundation for managing and optimizing voyages, as well as facilitating route selection, travel time estimation, and the adjustment of essential parameters to enhance efficiency (Fig. 1). The emulated vessel has the following characteristics:

Table 1. Vessel characteristics.

Characteristics	Value	Unit
Overall length	8.6	m
Molded beam	2.42	m
Depth	1.03	m
Design draft	0.34	m
Displacement	3.67	m
Maximum design speed	25	knots

Fig. 1. Main simulation model.

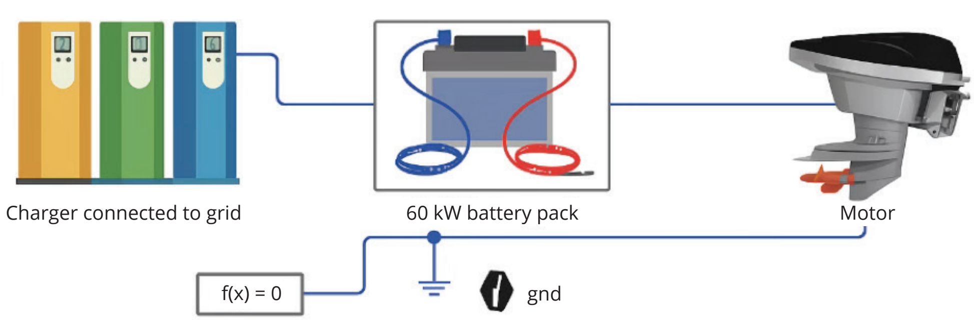
The design of the proposed propulsion system was developed in a Simulink simulation that models each vessel component with real parameters, providing an accurate and comprehensive representation of the system.

Sizing of the Vessel's Electric System

For sizing the motor power, it is necessary to calculate the brake power of the vessel as a function of speed. This power is derived from resistance tests conducted on the vessel, from which the total effective power versus speed curve is obtained. These tests considered the effects of wind and the motor operating margin.

Additionally, a sea safety margin (SSM) or additional resistance margin is included. This margin refers to a power reserve incorporated into the design of the vessel's propulsion system to compensate for the increased resistance caused by adverse sea conditions such as waves, wind, and strong currents.

Fig. 2. System of vessel components.



$$P_{E_{adjusted}} = P_E \cdot (1 + SSM) \quad (1)$$

Based on this adjusted effective power, the brake power of the vessel is calculated according to Equation (1).

$$P_B = \frac{P_{E_{adjusted}}}{\eta} \quad (2)$$

Where η is the overall efficiency of the power transmission system from the motor to the propeller. Efficiency η is broken down into components that represent the different efficiencies of the propulsion system elements. In *[MAN, 2012]*, the total efficiency is expressed as the product of several factors (HORSE), including:

- Hull efficiency (η_H): Accounts for the interaction between the hull, the water, and the propeller.
- Open-water propeller efficiency (η_O): Considers the performance of the propeller in open water.
- Relative rotative efficiency (η_R): Reflects the effect of the propeller's positioning behind the hull.
- Shaft efficiency (η_S): Represents losses in the transmission system, such as the shaft and gearbox.
- Motor efficiency (η_E): Depends on the motor design and operating conditions.

$$= \eta_H \times \eta_O \times \eta_R \times \eta_S \times \eta_E \quad (3)$$

Motor emulation

To emulate the electrical power consumed by the motor, a power-controlled load is used, calculated from the required speed versus brake power curve [7]. These data are loaded into a lookup table that receives the vessel's operating speed and outputs the required power for the controlled load. This load is connected to a DC bus through a power converter with defined efficiency.

Energy storage system

The energy storage system (ESS) is emulated using a lithium-ion battery modeled in Simulink [8], which includes parameters such as hysteresis and degradation. For this study, degradation was not considered since it lies outside the scope of the work. To protect the battery from over-discharge, the model's state of charge (SOC) output was used to disconnect it from the motor and end the simulation when necessary.

Port recharging system

The recharging system consists of a three-phase charger, which includes a current limiter that prevents overcharging and premature wear of the battery supplying energy to the motor. Energy recharging is managed appropriately, keeping battery levels within the assigned limits to avoid excessive discharges and ensure stable operation. The charger activates when the battery is discharged to 10% SOC and the vessel speed reaches zero; at that point, the charging system operates until the battery reaches 90% SOC.

The current limiter is calculated based on the charger power and battery voltage to prevent harmful overcharging:

- Charger power (P_C)
- Battery voltage (V_{bat})
- Current limiter (limitC)

$$\text{limitC} = \frac{Pc}{V_{bat}} \quad (4)$$

To estimate the approximate number of recharges required for the vessel to complete its route, both total system power and total battery energy are used:

- Total vessel power (*PT*)
- Total battery power (*PTB*)
- Number of recharges (*CR*)

Emulation of the vessel operational profile.

In the simulation, an operational profile was designed consisting of several navigation modes based on vessel speed, namely the maneuvering, economic, and maximum modes. Each mode operates at a specific speed range, which enables the vessel to complete the route, as illustrated in Fig. 3. Subsequently, a state machine was developed to represent the operation of the electric motor, varying according to the operational modes, the distance traveled, and the state of charge (SOC), as shown in Fig. 4. The state machine begins in the maneuvering mode and, after a certain time, evaluates the SOC and the distance traveled to transition to the economic mode. Once the proposed requirements are verified, it continues to the maximum mode and subsequently returns through the sequence until the motor speed reaches zero, at which point the cycle restarts, as depicted in Fig. 4.

Simulation results

Fig. 5 shows the curve of total effective power versus the speed obtained from the tests carried out on the vessel. Based on these data, the available power profile (blue) and the electric power consumption of the motor are obtained. To perform this scaling, the parameters presented in Table 2 are used.

Table 2. Scaled parameters.

Parameter	Value
η_E	2
η_S	2
SSM	2

According to these design requirements, a Deep Blue 50 RL/RXL motor manufactured by Torqeedo was selected. This motor has a rated power of 50 kW, a maximum efficiency of 89%, and a nominal voltage of 345 V. In addition, two 40-kWh battery packs (BMW i3 batteries) were selected and connected to provide a total voltage of 352 VDC. A 22-kW bidirectional charger was also included, allowing for efficient battery recharging based on the state of charge (SOC) while limiting the current to prevent overloads.

Fig. 3. Operational profile and traveled distance.

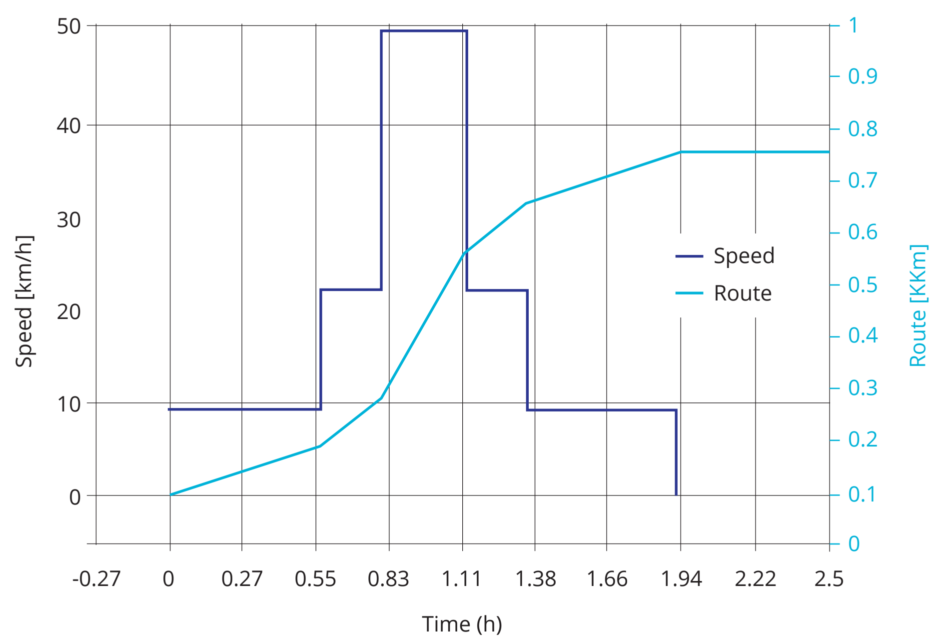


Fig. 4. Operational profile-based state machine.

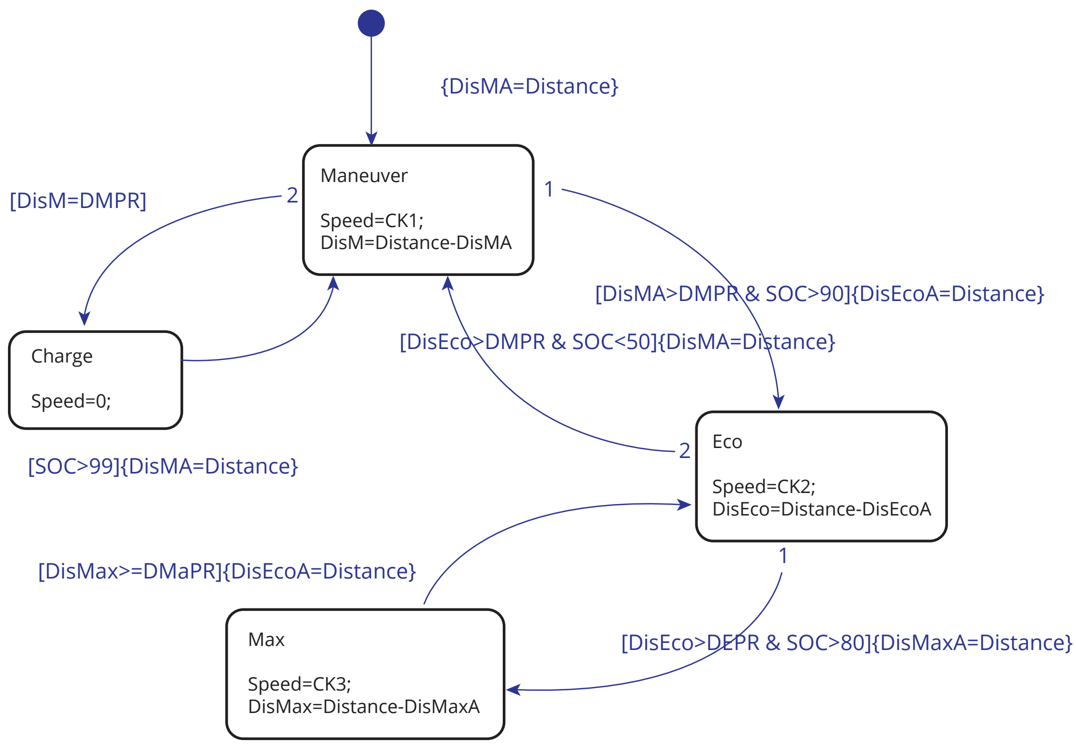
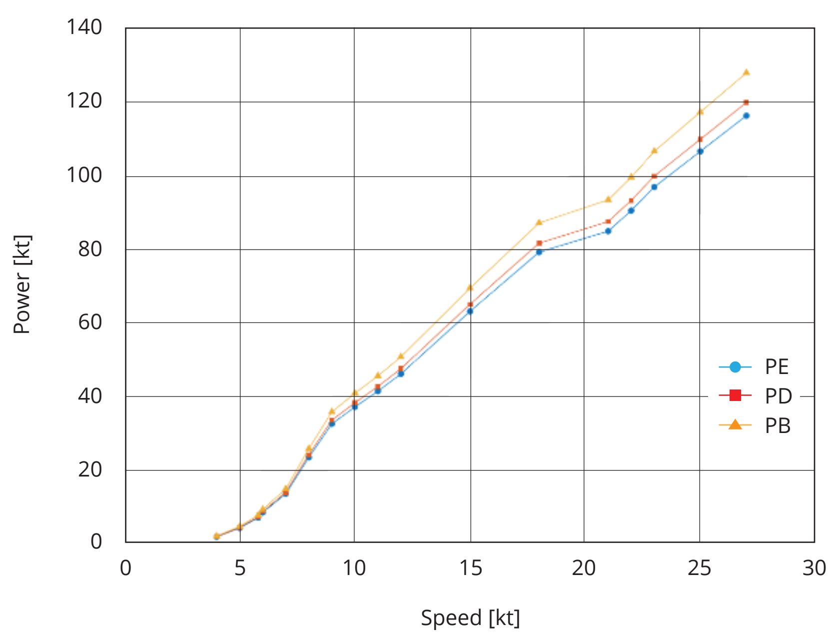


Fig. 5. Power vs Speed.



The simulation was carried out using a predefined route of 479 km and different operating speeds of 5 kt, 12 kt, and a maximum speed of 27 kt. For each speed, an operational profile was defined, ranging from 0% to 100%, indicating the proportion of time the vessel operates at each speed. These profiles were designated as maneuvering, economical, and maximum modes, respectively.

Subsequently, three simulations were conducted in which the operational profiles were varied, while maintaining the assigned route of 479 km:

1. Operational profile variation: maneuvering 20%, economical 20%, and maximum mode 60%.
2. Operational profile variation: maneuvering 0%, economical 0%, and maximum mode 100%.
3. Operational profile variation: maneuvering 0%, economical 0%, and maximum mode 100%.

The vessel completed the assigned route following the first simulation, using the selected operational profile, which included three speeds depending on the navigation phase. In maneuvering mode, the vessel maintained a speed of 5 knots (9.26 km/h) for a certain period; in economical mode, it operated at 12 knots (16.668 km/h); and in maximum speed mode, it reached 27 knots (50.004 km/h). The vessel followed the selected profile until its energy was depleted, requiring battery recharging before resuming the profile and continuing the route; in total, the vessel performed 13 recharging stops Fig. 6, optimizing energy consumption according to the selected operational profile.

Battery pack consumption along the selected route, starting with the battery at 100% state of charge, led to recharging up to 99% and discharging down to a minimum of 10%, as shown in Fig. 7. The selected route corresponds to the Atrato River trajectory, covering a total distance of 479 km with a travel time of 77.396 h, as illustrated in Fig. 8.

For the remaining simulations, the results are depicted in tables. Table 3 shows the results for the simulation with a maximum speed of 27 kt, while Table 4 presents the vessel performance results at 5 kt.

Fig. 6. Speed profile in the first simulation.

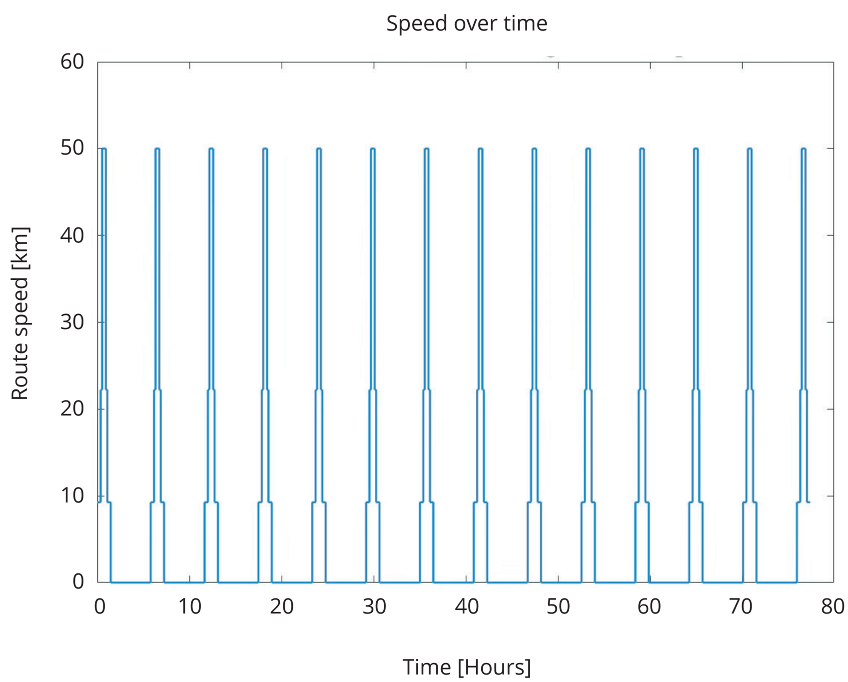


Fig. 7. State of charge (SOC) of the 80-kW battery in the first simulation.

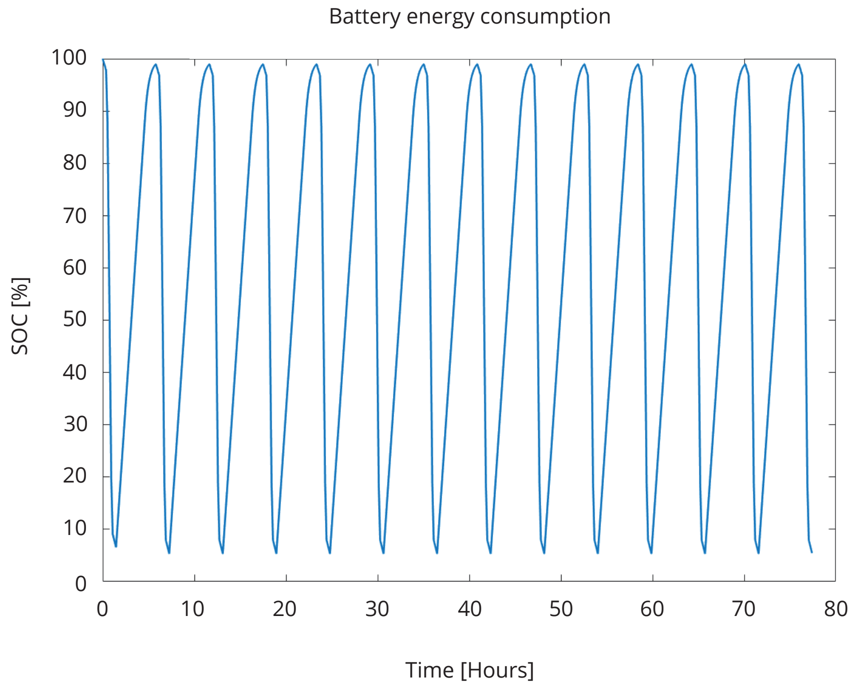
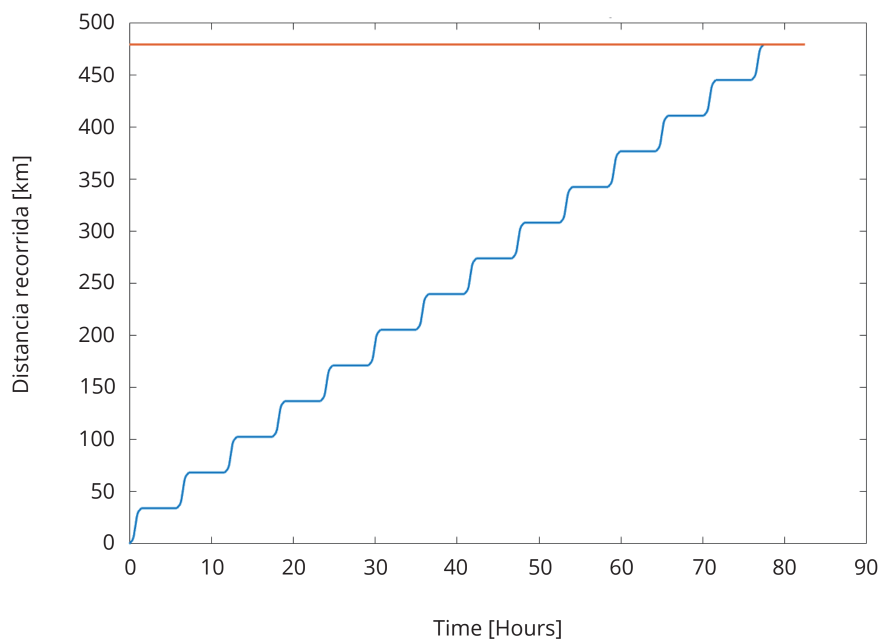


Fig. 8. State of charge (SOC) of the 80-kW battery in the first simulation.



Analysis of the results obtained

The power system modeled and simulated for small vessels was evaluated using MATLAB/Simulink simulations, considering three operating modes: maneuvering (5 knots), economical cruising (12 knots), and high-speed operation (27 knots). The results indicate that

Table 3. Vessel at 27kt maximum route speed.

Parameters	Value	Unit
Range	479	km
Recharge time	4.185	Hours
Number of stops	20	Count
Total recharge time	83.7	Hours
Total travel time	93.307	Hours
Travel without recharging	9.6011	Hours

Table 4. Vessel at 5kt minimum route speed.

Parameters	Value	Unit
Range	479	km
Recharge time	3.0786	Hours
Number of stops	3	Count
Total recharge time	9.236	Hours
Total travel time	60.965	Hours
Travel without recharging	51.72	Hours

the highest energy efficiency was achieved when operating exclusively in the economical mode, completing a 479-km route with only three charging stops and a total operating time of 60.96 hours. This behavior occurs because both the motor and the transmission system are streamlined for optimal cruising speed. In contrast, the high-speed configuration, although faster in terms of instantaneous velocity, required up to 20 charging stops to complete the same route, resulting in a total travel time of 93.30 hours. The operating profile shows that energy consumption increases significantly as power demand rises, bringing out the limitations of operating at high speeds in energy systems designed for long-distance travel. The lithium-ion battery-based energy storage system demonstrated robust and efficient performance, maintaining the state of charge (SOC) within a range of 10% to 90% across all simulations. This operational window prevents deep discharge cycles, reduces battery degradation, extends battery lifespan, and ensures system reliability. However, under high-speed operating conditions, the elevated energy consumption leads to a rapid decrease in SOC, requiring frequent recharging and negatively impacting overall system performance. These findings emphasize the need to enhance energy storage capacity or integrate renewable energy sources, such as solar panels or fuel cells, to improve system autonomy and reduce dependence on charging infrastructure.

The inverse relationship between operating speed and energy efficiency is consistent across all evaluated configurations. At higher speeds, particularly during acceleration phases, a spike in consumption of stored energy is observed, which reduces the range per charge and increases the stress on propulsion system components. These findings are consistent with previous studies that highlight the benefits of operating at optimal speeds to improve the efficiency of electric propulsion systems in inland vessels. Furthermore, comparisons with similar studies confirm that effective energy management strategies and appropriate selection of the operational profile are among the most critical factors in ensuring long-term operational and economic viability of electric vessels. These results also showcase the potential impact of this technology on sustainable inland waterway transportation. The effectiveness of the maneuverability index indicates that electric vessels are well suited for both short- and long-distance operations, meeting operational requirements while maintaining acceptable performance levels. Under these conditions, system autonomy is improved, payback periods are reduced, operational costs decrease, and overall system efficiency is enhanced. However, high-speed operation remains essential for specific demanding scenarios requiring rapid transit, although its feasibility strongly depends on charging frequency and infrastructure availability.

This study also underscores the importance of system-level simulation as an essential tool for the design and evaluation of energy systems. Simulation enables the identification of key limitations and improvement opportunities, providing a solid foundation for design optimization prior to real-world implementation. The results demonstrate that the proposed solution represents a practical and effective approach to reducing pollutant emissions and extending the operational lifetime of inland waterway transportation, particularly in regions such as Colombia, where rivers play a vital role in social and economic development. The adoption of clean technologies in this sector not only contributes to climate change mitigation but also fosters technological innovation and sustainable infrastructure development.

Conclusions

This work focuses on the design and simulation of electric propulsion systems for small vessels, with the aim of improving energy efficiency and reducing the environmental impact of inland waterway transportation. The electric propulsion system proposed and simulated in this study proves to be a practical and effective solution for enhancing river transport in terms of autonomy and operational longevity. The results indicate that the system operates more efficiently at low operating speeds (e.g., 5 knots), increasing vessel range and reducing the frequency of recharging cycles. This approach also contributes to lower emissions compared to internal combustion engines and strengthens the maritime industry’s commitment to the transition toward renewable technologies.

Matlab/Simulink simulation has demonstrated to be a powerful platform for analyzing and validating system performance, allowing the identification of key design parameters. This research establishes a framework for the future implementation of sustainable propulsion systems for small vessels and provides guidance for improving design methodologies and operational performance. Simulation results show that the proposed system meets the requirements of robustness and autonomy under different operating conditions, laying the groundwork for the development of practical solutions in the inland waterway sector. Furthermore, the data obtained enable design refinement and performance evaluation under real operating conditions, encouraging the adoption of renewable technologies in fluvial transport and promoting their integration into energy systems as an effective means of reducing the environmental impact of this industry.

Acknowledgements

This work came together thanks to the support of Instituto Tecnológico Metropolitano Institución Universitaria, which funded the “Young Researchers and Innovators” program. The study was also funded by the Francisco José de Caldas National Fund for Science, Technology and Innovation, provided by the Ministry of Science, Technology and Innovation through open call for proposals No. 938 of 2023 (program code 100864 and project code 105897).

Contributions

- Jose David Lopez Suarez: Simulations.
- Juan Pablo Villegas Ceballos: Data analysis, manuscript writing.
- Daniel Gonzalez Montoya: Supervision, final editing.
- Cristian Escudero Quintero: Manuscript writing, simulations.
- Edwin Giovanny Paipa Sanabria: Funding acquisition, final editing.

Founding source

This work was carried out with the support of the Instituto Tecnológico Metropolitano – Institución Universitaria, which funded the Young Researchers and Innovators program. Additionally, this study was financed with resources from the National Fund for the Financing of Science, Technology and Innovation Francisco José de Caldas, provided by the Ministry of Science, Technology and Innovation through Call 938 of 2023 (program code 100864 and project code 105897).

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