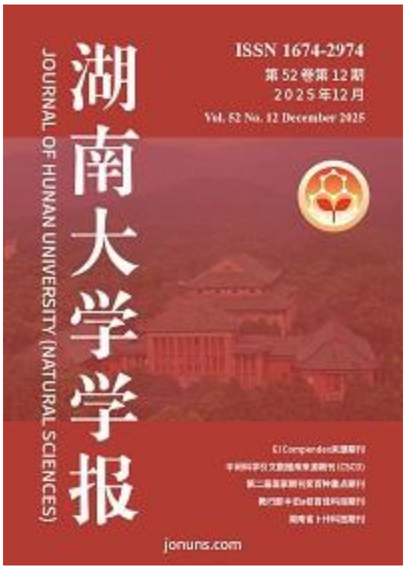

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Design and Simulation of a Green Hydrogen-Based Propulsion System for Colombian Navy Marine Vessels

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Abstract: This study develops and evaluates a green hydrogen-based electric propulsion architecture for small and medium maritime vessels, targeting the decarbonization of Colombian Navy operations while preserving autonomy and performance comparable to gasoline propulsion. The objective is to design and simulate a propulsion system powered by a proton exchange membrane fuel cell (PEMFC) and using supercapacitors for onboard energy storage in place of conventional batteries. A systematic engineering workflow was applied: the energy demand of a reference gasoline vessel was quantified, gasoline and hydrogen were compared on an equivalent usable-energy basis, hydrogen storage and component sizing were derived analytically, and a complete PEMFC powertrain was simulated in MATLAB/Simscape under a representative maritime drive cycle and compared against theoretical calculations. For a baseline of 600 gallons of gasoline, the required energy was 24,420 kWh (17,094 kWh at 70% efficiency). The equivalent hydrogen mass was 733.33 kg H_2 (513.33 kg at 70%), requiring 1.65 m^3 storage volume versus 2.27 m^3 for gasoline (18% reduction) and 733.3 kg fuel mass versus 1704 kg (57% reduction). A cost comparison indicated higher fuel cost for hydrogen (USD 2794) than gasoline (USD 2155). Simulations reproduced expected PEMFC behavior under the drive cycle, with stable temperature below 80°C and load-dependent current–voltage–power responses. The novelty is the integrated replacement of battery-based storage with supercapacitors in a hydrogen PEMFC maritime propulsion system, enabling high power density and rapid transient response for realistic marine operation.

Keywords: Green hydrogen; Marine propulsion; PEM fuel cell; Supercapacitors; Energy efficiency; MATLAB/Simscape; Decarbonization.

哥伦比亚海军舰艇绿色氢能推进系统的设计与仿真

摘要：本研究面向中小型海上船舶，构建并评估一种以绿色氢为能源的电推进体系，旨在在保持与汽油推进相当的续航与动力性能的同时，实现哥伦比亚海军舰艇运行的低碳化。研究目标是设计并仿真一种以质子交换膜燃料电池（PEMFC）为动力源、以超级电容替代传统电池作为船载储能单元的推进系统。研究采用系统化工程流程：量化基准汽油船舶的能量需求；在等效可用能条件下比较汽油与氢能；通过解析计算完成氢储存与关键部件选型/定容；并在 MATLAB/Simscape 平台上，基于具有代表性的海上航行工况（drive cycle）对完整 PEMFC 动力系统进行仿真，并与理论计算结果对比验证。以 600 加仑汽油为基准，所需能量为 24,420 kWh（按 70%效率计为 17,094 kWh）。等效氢气质量为 733.33 kg H_2（按 70%效率计为 513.33 kg），所需储存体积为 1.65 m^3，低于汽油的 2.27 m^3（降低 18%）；燃料质量为 733.3 kg，低于汽油的 1704 kg（降低 57%）。成本比较显示氢燃料费用（2794 美元）高于汽油（2155 美元）。仿真结果再现了 PEMFC 在工况循环下的预期行为：温度稳定低于 80°C，电流—电压—功率响应随负载变化。本文创新点在于在氢能 PEMFC 海洋推进架构中，以超级电容对电池储能进行 体化替代，从而实现高功率密度与快速瞬态响应，满足真实海上运行需求。

关键词：绿色氢能；船舶推进；质子交换膜燃料电池；超级电容；能效；MATLAB/Simscape；脱碳。

1. Introduction

As an organization responsible of the maritime protection, the Colombian Navy has been tasked with safeguarding the environment according to the PDN (2042)[1], including the responsibility to reduce greenhouse gas emissions across its fleet of vessels. Currently Colombian Navy has different Sea Units that use gasoline-powered propulsion systems. Over the years, the CO2 amounts have been gradually increasing in Colombia, reaching values of 101 million tons of carbon dioxide (CO2) in 2025 [2].

The most contribute sectors to these emissions are: transportation, with approximately 40%; followed by the industrial sector with 20%; and, the electric power and heat sector, also with 20%. It is estimated that a reduction of approximately 2.3 m CO2/year is needed to achieve carbon neutrality by 2050, which is equivalent to reduce 3.1% annual of total emissions generated [3][4][5][6].

Alternative energies, such as hydrogen technologies, have significant potential to grow in Colombia. Hydrogen is a versatile and promising energy carrier that can be produced from a variety of sources, including fossil fuels, water, biomass, nuclear energy, and others. However, these technologies still face major technical obstacles, mainly low efficiency, short catalyst lifespan, high costs, and scaling difficulties, that must be solved before hydrogen production can become truly viable and widely adopted. [7][8][9].

According to the Hydrogen Roadmap for Colombia 2025[10], three types of hydrogen are identified: hydrogen from fossil fuels, hydrogen from electricity and hydrogen from fossil fuels with CCUS or blue hydrogen. In short, green hydrogen seems to be the quickest, most sustainable, and efficient option for Colombia. Blue hydrogen could also be important if oil and gas companies take advantage of capturing carbon dioxide and help make it widely used[11][12][13][14].

This simulation explores how this technology could be used in small patrol vessels, such as the Apostle Type Units of the Colombian Navy's Coast Guard, shown in Figure 1. MATLAB, within the Simscape environment, is used to closely study how gases behave inside PEM fuel cells, providing a clear picture of how the system would perform in real-world conditions[15].

Figure 1. Colombian Army Vessel - U.R.R. Apostle (Source: developed by the authors)

Integrating these models into Simscape enables a more comprehensive evaluation of PEM fuel cell performance by considering multiple variables. It allows detailed analysis of factors such as temperature, thermal efficiency, and reactant utilization, providing a holistic approach to the design and optimization of these systems[16][17].

We simulate the integration of supercapacitor packs, also known as ultracapacitors or electric double-layer capacitors (EDLCs)[18] with Li-ion battery packs, highlighting their emergence as a promising hybrid energy storage solution. They stand out for several key advantages, such as energy saving and environmental protection, high power density, fast charging and discharging, and long lifetime, allowing to improve the energy density and efficiency of supercapacitors, fulfilling all the aforementioned characteristics[19][20][21].

Another key point to analyze is how efficiently hydrogen can be stored compared to the gasoline currently used in Colombian Navy vessels, especially in terms of how much energy it provides per kilogram (gravimetric density) and per liter (volumetric density).

The stored hydrogen is subsequently used as fuel in Proton Exchange Membrane Fuel Cells (PEMFC) to generate electricity through electrochemical oxidation [22][23].

By applying the stored hydrogen in these fuel cells[24][25], a chain reaction is initiated causing current between their poles, this process allows an efficient conversion of the chemical energy of hydrogen into electrical energy. In addition, PEMFCs[26] widely recognized for their high electrical efficiency, rapid start-up capability, and near-zero emissions when operated on pure hydrogen, represent one of the most attractive technologies for maritime applications. Their ability to directly convert compressed or liquefied hydrogen into electrical energy with only water as the primary exhaust product makes PEMFCs an exceptionally versatile and environmentally sustainable solution for both propulsion and auxiliary power generation in naval vessels. [27][28]29].

The research object, Green Hydrogen-Based Propulsion System for Colombian Navy Marine Vessels, integrating PEM fuel cells and supercapacitors was selected based on technical, environmental, and operational considerations relevant to modern marine transport. Conventional small and medium-sized gasoline-powered vessels were used as a reference due to their widespread application, significant emissions, and well-known performance profiles, enabling quantitative comparison with alternative technologies. Green hydrogen was chosen for its high energy density and zero-emission operation, while PEM fuel cells, shown in Figure 2, were selected for their efficiency and suitability for marine use. Supercapacitors were adopted for their high power density and durability, allowing effective management of transient loads. This configuration enables comprehensive theoretical and simulation-based performance evaluation.

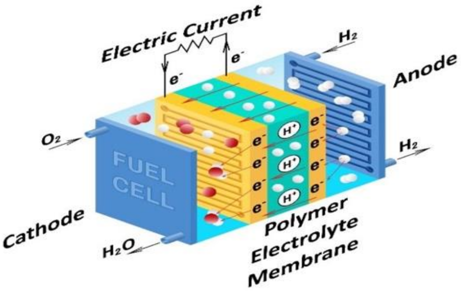


Figure 2. Fuel cell PEM [30]

2. Methodology

The study employed a systematic engineering and simulation-based methodology to evaluate a hydrogen-powered maritime propulsion system, shown in Figure 3. First, the operational characteristics and energy requirements of conventional gasoline-powered vessels were analyzed as a reference. Next, green hydrogen, PEM fuel cells, and supercapacitors were selected based on efficiency, power density, and environmental criteria. Analytical models were developed to calculate energy demand, storage capacity, system weight, and efficiency, enabling comparison with gasoline systems. A complete propulsion architecture was then designed and simulated under realistic marine operating conditions. Finally, simulation results were validated against theoretical calculations to assess performance, feasibility, and scalability.

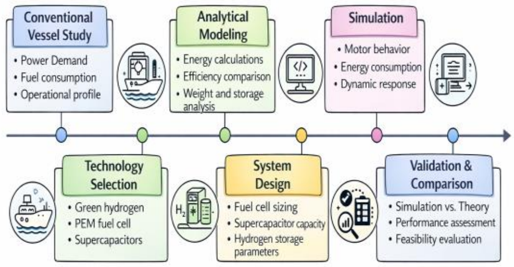


Figure 3. Steps involved in conducting the study (Source: developed by the authors)

Before running the simulation, it is essential to properly size the hydrogen storage system and choose the right tank materials to achieve the desired energy density, both by weight and volume. The first step is to calculate how much hydrogen is needed to match the usable energy currently provided by the vessel's gasoline. Using hydrogen's lower heating value of 33.3kWh/kg (120 MJ/kg), we can directly convert the vessel's energy needs into the corresponding hydrogen mass. This method provides a clear and accurate way to compare the two energy sources on an equal footing.

Subsequently, an efficiency factor of 70%, assumed to be consistent across both systems, is applied to convert hydrogen consumption into equivalent electrical energy. Based on this, the required hydrogen volume can be estimated. Considering hydrogen's density and the designated storage pressure, the optimal size of the storage tank is then calculated. It is known that each of the three outboard engines (F/B) consumes 31.7 gallons per hour. These parameters form the basis for the calculations presented in. (1):

$$Pt = \frac{Cg * E}{1\ gal} \qquad (1)$$

Where:
Cg = Gasoline Consumption x hour x 03 F/B = 95.1 gallon
E = Gasoline electric power x hour in 1 gallon
Pt = Total electrical power

2.1. Conversion of Hydrogen Consumption to Electric Power

Since the electrical energy required to simulate the fuel switch from gasoline to hydrogen is found according to Table 1, it is assumed to be the same electrical energy required for H2. Therefore, it is searched what is the amount of hydrogen needed to provide the same energy, and this result is shown using (2). Therefore, 733.33 kgH2 is needed and, considering an efficiency of 70% of the internal combustion engine, the required amount of H2 is reduced to 513.33 kg.

Table 1. Gasoline electric power (Source: developed by the authors)

Power kWh (hour)	Power kWh (Total)	Power kWh (Total to 70%)
3,870.57 kWh	24,420kWh	17,094 kWh

$$x = \frac{1\ \mathrm{kg}H_2 * \mathrm{Pt}}{33.3\ \mathrm{kWh}} \qquad (2)$$

2.2. Hydrogen tank size

Now, these values are substituted into (3) to find that the volume of the tank is: 1.65 m^3.

$$v = \frac{n(mol) * R\left(8.314 \frac{J}{mol * K}\right) * T(K)}{p(pascal)} \qquad (3)$$

Then, using (4), the weight of the tank with 2,475 kg is calculated, where:

Pth = Hydrogen tank weight
Dfc = Carbon fiber density

$$Pth = v \times \mathrm{Dfc}\left(1{,}500 \frac{kg}{m^3}\right) \qquad (4)$$

2.3. Superconductor capacitance

Since the total power of hydrogen is 17,094 kWh and according to (5) the energy expressed in mega joules can be converted to 61,538.4 MJ, this to be used in (6) and to know the total capacitance of the supercapacitors of the batteries of the system with 21F.

$$E = Pt(70\ \%) * 3{,}6 \frac{MJ}{kWh} \qquad (5)$$

Since the total navigation time is 7 hours expressed in seconds, this gives 25,200 seconds.

$$C = \frac{2 * E}{V^2 * t} \qquad (6)$$

2.4. Battery size

Equation (7) define the number of supercapacitors required. For this application, the required number, denoted as CT, is 4.

$$CT = \frac{C}{10F} \qquad (7)$$

Based on the available data, the system's total weight including hydrogen, its storage tank, and batteries is calculated to be 2,475.3 kg, using the datasheet estimate for the supercapacitor mass (0.1 kg). To initiate the analysis, a simulation model of hydrogen electrolysis using polymer electrolyte membrane (PEM) fuel cells is developed with the Simscape library, as shown in Figure 3.

This PEM system generates clean electricity through proton exchange, which produces electrons. To evaluate consumption behaviour, a drive cycle representative of a sea boat's operation was implemented as the system's load profile. This consumption pattern is depicted in Figure 4.

Based on the sizing calculations, the total mass of the hydrogen subsystem, including the compressed hydrogen, the Type IV storage tank, the lithium-ion battery pack, and the supercapacitor module (0.1 kg according to datasheet), amounts to 2,475.3 kg.
Subsequently, a dynamic simulation model of the complete PEM fuel cell powertrain was implemented in MATLAB/Simscape, as depicted in Figure 4.

The PEMFC system generates clean electricity through the electrochemical oxidation of hydrogen, with protons migrating through the polymer electrolyte membrane and electrons flowing through the external circuit, producing only water and heat as byproducts.
To evaluate the real-world energy consumption and power response of the system, a representative maritime drive cycle (power demand profile of a Colombian Navy patrol vessel) was applied, with the resulting demand profile and system behavior shown in Figure 5.

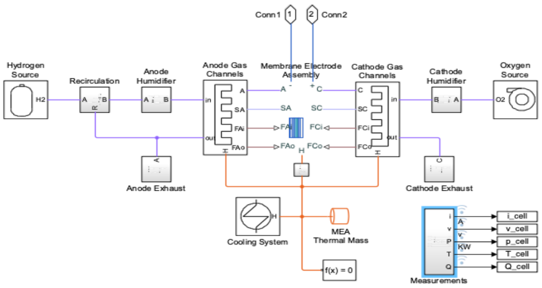


Figure 4. PEM cell electrolyzer [12]

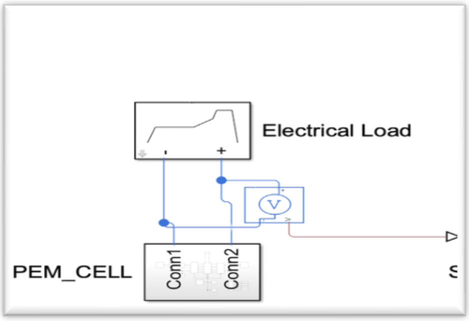
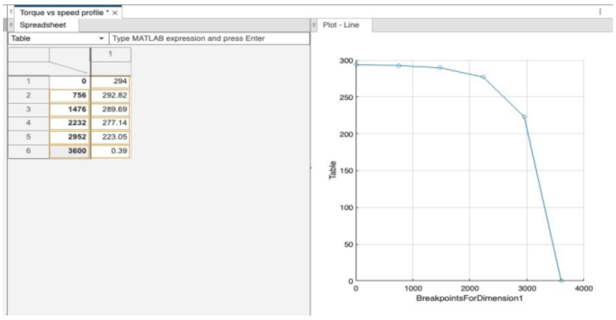


Figure 5. Drive cycle (Source: developed by the authors)

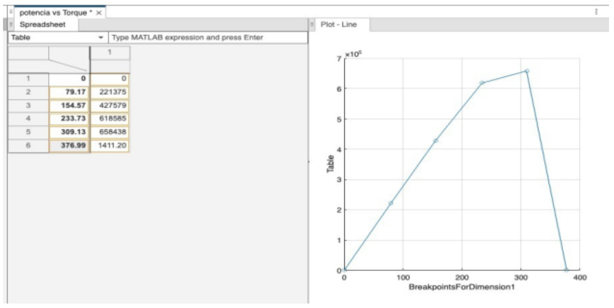
The required electric motor is verified based on the calculated electrical power presented in Table 1. To assess its performance, the manufacturer's graph shown in Figure 6 is consulted, and the motor's behavior is plotted in Figure 7, illustrating mechanical power versus speed in radians per second. This enables an interpolation using the electrical power derived from the consumption cycle of the Rapid Reaction Unit of the Colombian Navy.

Following this, the system is connected to the inverter, and the electric motor is simulated using the manufacturer's specifications. This simulation yields the power curves of the propulsion system. The configuration and connections used in this setup are illustrated in Figure 8 and Figure 9.



		1
1	0	294
2	756	292.82
3	1476	289.69
4	2232	277.14
5	2952	223.05
6	3600	0.39

Figure 6. Torque vs RPM graph (Source: developed by the authors)



		1
1	0	0
2	79.17	221375
3	154.57	427579
4	233.73	618585
5	309.13	658438
6	376.99	1411.20

Figure 7. Power mechanical vs pi/s graph (Source: developed by the authors)

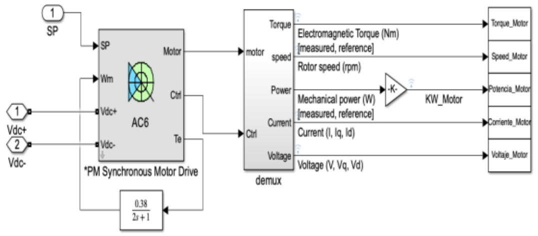


Figure 8. AC6 Verification unit AC (Source: developed by the authors)

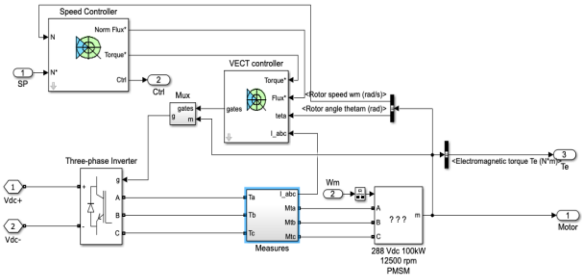


Figure 9. AC and Motor Connection (Source: developed by the authors)

3. Results

At the end of the investigation, significant results have been obtained. With a quantity of 600 gallons of gasoline, it was possible to demonstrate the amount needed to achieve the energy efficiency required for the F/B engines. The findings show a reduction in the volume needed, with a difference of 18% compared to the gasoline traditionally used. In addition, a notable decrease in weight was observed, reaching 57% less compared to conventional fuel, these data are evidenced in Table 2.

Table 2. Comparison of hydrogen and gasoline (Source: developed by the authors)

	Volume (m^3)	Volume (%)	Energy efficiency (Kwh)	Weight (Kg)	Weight (%)
Gasoline	2.27	100	24,420	1704	100
Hydrogen	1.65	82	24,420	733.3	43

It is also evident that having 600 gallons of gasoline versus 733,3 kg of hydrogen has a cost that is evident in Table 3. In this specific case, the total cost of hydrogen is higher than the total cost of gasoline. However, it is important to consider other factors, such as efficiency and environmental impact, when making decisions on which fuel to use. In addition, according to Colombia's roadmap for sustainability, the aim is to lower the cost of H2 to below US$2. According to studies conducted at the Universidad Javeriana in Colombia, there are currently laboratory production costs of 3,07 USD/kg to 1,81 USD/kg, which would achieve a decrease in production costs.

Table 3. Cost comparison (Source: developed by the authors)

Gasoline	Hydrogen
USD 2155	USD 2794

The results of the simulation are shown below, so the behavior of the PEM cell with the consumption cycle will be analyzed in two parts, where the operation of the system is evidenced.

3.1. Simulation of PEM Cells with Consumer Cycle Load

Figure 10 shows the current consumption and Figure 11 shows the voltage behavior of the PEM cell according to the consumption cycle of a boat at sea and Figure 12 shows the behavior of the power consumption per motor. Figure 13 shows a stable temperature behavior with values below 80 ºC, complying with a temperature control according to physical models of the PEM cells.

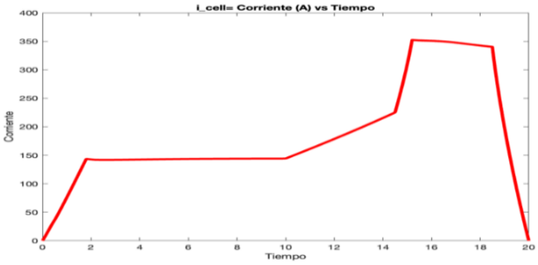


Figure 10. Load current (Source: developed by the authors)

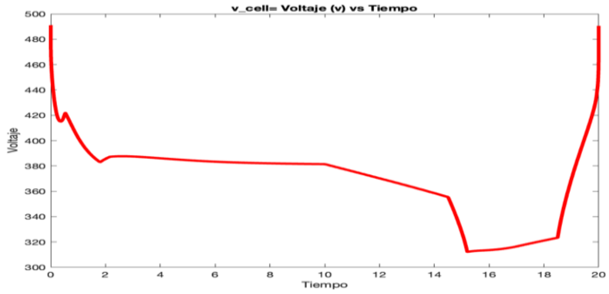


Figure 11. Load voltage (Source: developed by the authors)

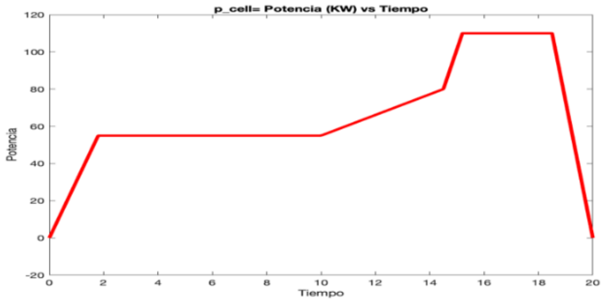


Figure 12. Power of a motor (kW) of load vs time (s) (Source: developed by the authors)

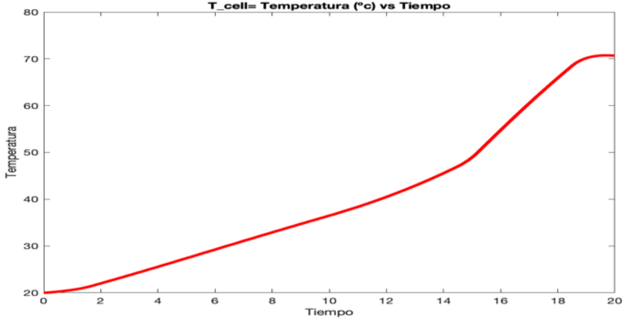


Figure 13. Load temperature (°C) vs time (s) (Source: developed by the authors)

From a practical perspective, the results show that combining PEM fuel cells with supercapacitors provides a feasible and scalable propulsion solution for small and medium-sized maritime vessels. Replacing conventional batteries enhances power management in dynamic operating conditions, allows fast response to transient loads, reduces component degradation, and extends system lifetime. The system design and simulations offer practical guidelines for hydrogen storage, material selection, and energy management, supporting real-world deployment. Environmentally, the proposed architecture enables significant reductions in emissions while meeting maritime decarbonization targets. Theoretically, the study validates fuel cell–supercapacitor synergy, strengthening hybrid energy modeling and advancing system-level design methodologies for sustainable marine propulsion.

4. Discussion

This discussion contextualizes the proposed hydrogen-powered maritime propulsion architecture within current decarbonization efforts, emphasizing the implications of replacing batteries with supercapacitors. The results are examined in terms of performance, efficiency, durability, and environmental impact, highlighting how integrated fuel cell–supercapacitor systems can address operational limitations of conventional marine propulsion technologies.

4.1. Simulation of Electric Motor Behavior

Figure 14 shows the result of the entire propulsion system, where in the Scope PMSM Drive the behavior of an electric motor can be observed with respect to the driving cycle of the boat. The simulation of an electric motor is made for ease of results, because it is a system that consumes too much processing resource, but the calculations are made for 04 three-phase electric motors, each of 440 V, 110 KW, 250 A and 2 poles.

Figure 15 shows that the system design behaves with the necessary power according to the calculations of the motor required, which was a power of 110 KW, complying in the same way with the behavior cycles of a boat at sea.

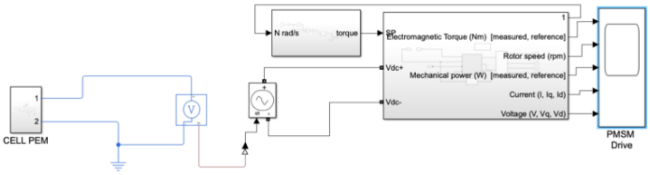


Figure 14. Electric Propulsion System (Source: developed by the authors)

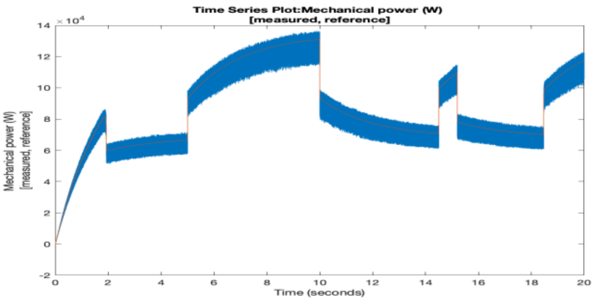


Figure 15. Mechanical System Power (Source: developed by the authors)

System shows a behavior directly influenced by the requirements of the consumption cycle designed for a marine vessel. Figure 16 and Figure 17 show this behavior of the electric motor, where a direct dependence on the performance and capabilities of the direct power supply is observed. This highlights the importance of having a reliable and efficient power supply to ensure optimal system performance.

Figure 16 shows the torque required in the system, which is 588 Nm to comply with the normal behavior according to the Driving Cycle graph of the vessel. It is observed that when the RPM is zero, the torque in the system is maximum. Figure 17 shows the accelerations and decelerations of the system according to the behavior of the boat at sea, thus demonstrating the behavior of an engine with the required power and torque.

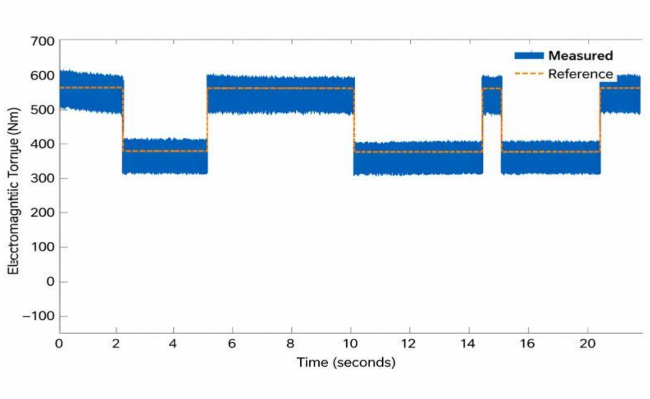


Figure 16. System torque (Source: developed by the authors)

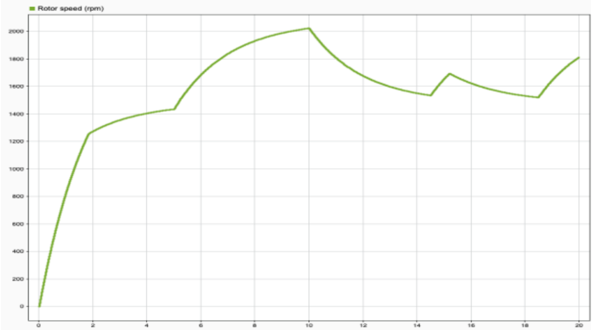


Figure 17. System speed (Source: developed by the authors)

Figure 18 shows the behavior of the vessel used as a sample to demonstrate the performance of the electric propulsion system designed with fuels such as green hydrogen. This provides a solid basis for future research on clean energy propulsion systems.

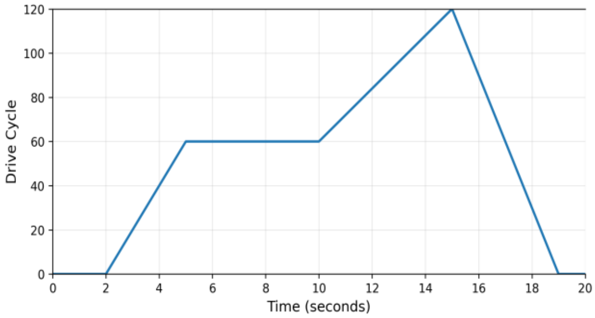


Figure 18. Drive cycle (Source: developed by the authors)

Finally, Table 4 shows the differences caused using supercapacitors in a three-phase electrical system.

Table 4. System differences (Source: developed by the authors)

Appearance	With Supercapacitors	Direct Feeding
Instantaneous discharge capability	High instantaneous discharge capacity for power peaks	Depends on the direct power supply
Efficiency in charge and discharge cycles	High efficiency in charge and discharge cycles	N/A
Recharge time	Fast reloads.	N/A
Dynamic response	Fast torque and speed response	Depends on the direct power supply.
Stability of power delivery	Stable energy delivery over time	Stability depends on the direct power supply.
Thermal inertia and reactivity	Lower thermal inertia and reactivity	Depends on the direct power supply
Life cycle	Longer life cycle in terms of charge and discharge cycles.	N/A.
Weight and space	Lighter and takes up less space	Lower weight and space requirements since there are no batteries or supercapacitors

5. Conclusion

The amount of hydrogen needed to achieve energy efficiency in F/B engines is smaller in both volume and weight compared to conventional gasoline. This makes hydrogen an excellent choice for energy storage and transport in marine applications, improving overall efficiency. Its lightweight and compact form not only simplifies logistics but also reduces operating costs. Thanks to its high energy density and sustainable nature, hydrogen is emerging as a promising alternative for navigation, helping to lower environmental impact. In this way, hydrogen offers both an efficient and eco-friendly solution for the maritime sector, supporting the shift toward cleaner and more sustainable energy sources.

At present, hydrogen is more expensive than gasoline. However, research suggests that production costs could fall significantly in a near future. As technologies improve, hydrogen may become a more economically competitive option. Innovations in efficient, cost-effective production processes, along with infrastructure development, are expected to make hydrogen more accessible and affordable. Over time, this could allow hydrogen to compete with gasoline and establish itself as a practical and sustainable energy source.

While cost is an important factor, environmental impact and sustainability are equally critical when choosing a fuel. Hydrogen has clear advantages: it reduces emissions and supports the transition to cleaner energy. Using hydrogen in propulsion systems can lower carbon footprints and improve energy efficiency, contributing to a greener future. Being a renewable energy source, it also drives innovation in sustainable technologies. Evaluating hydrogen not just economically but also for its environmental benefits is essential for promoting responsible and forward-thinking transport solutions.

As production costs decline, hydrogen's environmental appeal will only grow. Greater accessibility and technological advances will encourage broader adoption as a clean, sustainable energy source. This progress would strengthen hydrogen's role in the global energy transition, significantly reducing emissions and promoting a more efficient and eco-friendly future. By making hydrogen more affordable and scalable, industries and governments can integrate it into energy systems, decreasing reliance on fossil fuels. Ultimately, improved production methods will accelerate decarbonization, help achieve climate goals, and support a cleaner planet. The shift to hydrogen has the potential to reshape energy landscapes, ensuring long-term sustainability and a lower environmental impact.

This study presents an original maritime propulsion architecture that replaces batteries with supercapacitors in a hydrogen-powered system. Unlike conventional battery-based approaches, it highlights improved power density, durability, and dynamic load response. Through integrated theoretical modeling and simulation, the work extends existing energy frameworks and provides a reference design for sustainable, high-performance marine propulsion research.

Based on the study results, designers of small and medium-sized vessels are encouraged to adopt hybrid PEM fuel cell–supercapacitor systems to enhance dynamic power management and reduce degradation.

Supercapacitor sizing should target transient loads, while hydrogen storage must balance safety, weight, and autonomy. Future research should focus on prototype-scale testing, long-term marine durability, advanced energy management strategies, and comprehensive techno-economic and life-cycle assessments.

Declarations

Author Contributions

Conceptualization, formal analysis, and writing—review and editing Naranjo-Lourido W., Olaya-Vera O.E., Tibocha-Gomez J.L., Martinez-Baquero J. and Carvajal-Carvajal J.R.; methodology, validation, investigation supervision, project administration, and data curation Naranjo-Lourido W., Olaya-Vera O.E., Tibocha-Gomez J.L. and Martinez-Baquero J; writing—original draft preparation and visualization Naranjo-Lourido W., Olaya-Vera O.E., Tibocha-Gomez J.L. All authors have read and agreed to the published version of the manuscript.

Data Availability Statement

The data presented in this project are available on request from the corresponding author.

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Informed Consent Statement

The study was developed with the prior signed consent of the participants

Conflicts of Interest

The author declares that there is no conflict of interests regarding the publication of this manuscript. In addition, the ethical issues, including plagiarism, informed consent, misconduct, data fabrication and/or falsification, double publication and/or submission, and redundancies have been completely observed by the authors.

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