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Technical Assessment of Diesel-to-Hydrogen Hybrid Propulsion Conversion in Nautical Vessels: Energy Performance, Operating Costs, and CO_2 Reduction

Guilherme Ianusckiewicz Marques

USP – Department of Mining and Petroleum Engineering – Polytechnic School
Av. Professor Mello Moraes, 2373 - Butantã, São Paulo - SP, 05508-030, Brazil.

E-mail: alexguimarques@hotmail.com
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Abstract: The study evaluated the conversion of diesel propulsion systems to hybrid configurations with hydrogen fuel cells in three nautical vessels: the Ferretti 72ht, Ferretti 660, and Intermarine 600 Full. Fuel consumption, costs (Capex and Opex), and carbon dioxide emissions were analyzed, with results presented in seven tables that included operational performance, annual savings, installation and maintenance costs, carbon credits, and economic viability. The results demonstrated significant reductions in diesel consumption, ranging from 8.13% to 16.06%, equivalent to 10 to 31 liters per hour, with annual savings of US$ 266.904.00 and a reduction in CO_2 emissions of 447.66 tons per year. The Santos–Paraty route was also analyzed, where the conversion to the hybrid system resulted in a reduction of 304 liters of diesel per trip across the three vessels, with financial savings of US$ 485.88 and the avoidance of 815 kg of carbon dioxide emissions. The total cost of installing the cells was US$ 6.781.02, with an estimated lifespan of 10 years, resulting in an annual net Capex of US$ 678.10. The operational costs of refilling were US$ 37.71, maintenance US$ 20.47, and carbon credits US$ 40.74/year. The annual diesel savings of US$ 486.40 made the Opex US$ - 468.96. The estimated payback period was 14.5 years. It is concluded that conversion to hybrid fuel systems is technically feasible, economically advantageous, and environmentally sustainable, offering an effective alternative to reduce carbon emissions and costs in the nautical sector.

Keywords: Hydrogen fuel cell; Energy efficiency; Hybrid propulsion; Emissions reduction; Sustainable maritime transport.

1. INTRODUCTION

The maritime industry is an important part of global trade, accounting for between 80% and 90% of all cargo [1, 2]. However, this logistical importance comes with a challenge, as the sector is also a major source of greenhouse gas (GHGs) emissions, contributing around 2.7% to 3% of carbon dioxide released globally [3, 4]. Therefore, the search for sustainable alternatives in the nautical sector has gained great relevance and is becoming increasingly prominent in the environmental transformation process [5, 6].

Although maritime transport generates a relatively smaller environmental impact compared to other modes, there is increasing pressure to adopt more sustainable practices, including the use of environmentally friendly fuels and compliance with stricter environmental regulations. Despite technological advances, the long-term effects of these changes still require more detailed and continuous evaluation [7, 8, 9].

Greenhouse gases (GHGs) are natural components of the atmosphere that trap heat and help maintain Earth's temperature at levels suitable for life. The main contributors to global warming are carbon dioxide (CO_2), methane (CH_4), and nitrous oxide (N_2O). However, since the Industrial Revolution, human activities such as the burning of fossil fuels have increased their concentration, exacerbated global warming and promoting climate change [10, 11, 12]. Reducing carbon dioxide emissions from global shipping represents a major challenge. Between 2007 and 2012, shipping released approximately 1.038 billion tons of greenhouse gases (GHGs) per year [13]. Knowing that the sector is highly dependent on the use of fossil fuels, the International Maritime Organization (IMO) [14], in an effort to reduce this impact, proposed annual reduction targets for these emissions of at least 20%, with an ambition to reach 30%, and by 2030 they should be reduced by at least 70%, to reach 80%, compared to the baseline year of 2008.

The International Energy Agency (IEA) [15] highlighted hydrogen as one of the most promising energy sources to help reduce carbon emissions worldwide. This is due to hydrogen's ability to store and supply renewable energy without releasing carbon dioxide during its energy conversion; thus hydrogen fuel cells appear as an innovative technology to produce clean energy, being efficient and without emitting polluting gases directly into the environment [16].

The use of hydrogen as fuel appears as a promising alternative for reducing the use of fossil fuels [17, 18, 19] and, in this way, assumes a central position for a more sustainable energy future [20, 21]. Several studies demonstrate the potential of hydrogen in maritime propulsion, combining operational efficiency and compliance with environmental regulations, even though its use is still in the early stages of development [22, 23, 24]. To achieve the desired objectives of this technology, a structure is needed that includes government incentives and investments in research and development, as well as the creation of appropriate standards and regulations [25], thus, the increased use of hydrogen can generate significant geopolitical discussions, with the potential for changes in global energy, economic, and strategic relations [26].

The objective of this work is to evaluate the impact of converting conventional propulsion systems to hydrogen hybrid systems, considering aspects of energy efficiency, range, and operational performance of the vessel, based on a comparison of fuel consumption and pollutant emission data before and after the conversion. In this way, the study contributes to the advancement of knowledge about the application of hydrogen fuel cells in the nautical sector, offering a detailed technical evaluation of the performance gains and emission control resulting from the adoption of this technology.

2. METHODOLOGY

2.1. General procedures and characterization of the hybrid system

The conversion of vessels to use hydrogen fuel cells represents a promising alternative to reduce the consumption of fossil fuels and decrease atmospheric emissions. In this study, three medium-sized vessels were converted to operate with hybrid technology (diesel + hydrogen fuel cell).

The fuel cell used in this study is the WR Marine model, developed by Hybrid International, illustrated in Figure 1, and used for nautical applications and light diesel. It operates with a nominal voltage of 12 V, a current of 3 A, and a power of 36 W (0.036 kW), the hydrogen refill has an autonomy of 30 h of continuous operation, and the body is manufactured in engineering ABS plastic, with a completely marine system, suitable for high humidity and salinity environments [27].

Figure 1. Hydrogen fuel cell WR Marine model.

2.2. Diesel cost and reference value

The cost of diesel used in the analyses was obtained through a direct survey at a nautical refueling station located in the region of the experiment, as illustrated in Figure 2. The value of US$ 1.60 per liter (October 2024) was used as a reference for calculating fuel costs and analyzing the reduction in vessel costs after the installation of the fuel cell.

Figure 2. Nautical refueling station.

2.3. Features of speedboats

2.3.1. Ferretti 72ht speedboat

The speedboat, illustrated in Figure 3, has a total length of 22.3 m and a maximum beam of 5.6 m. It is equipped with two MTU V8 1200 engines, each with 1,200 HP (882 kW at 2,300 rpm), 1,150 CV, and a maximum torque of 4,010 N×m between 1,200 and 2,100 rpm. The tank holds 3,700 l. Conventional diesel consumption is 123 l/h, and consumption after hybrid conversion is 113 l/h.


Figure 3. **Ferretti 72ht** speedboat.

2.3.2. Ferretti 660 speedboat

The speedboat is 19.98 m long, 5.53 m wide, and has an estimated displacement of 43.2 t, a maximum torque of 3,359 N×m (2,300 rpm), a fuel capacity of 2,270 liters, and two MAN V10 1100 CR engines with 1,100 HP each, totaling 1,115.26 HP (Figure 4).


Figure 4. Position of the hydrogen fuel cells in the cockpit.

Diesel tank capacity 162 l/h, after hybrid conversion 145 l/h, as shown in Figure 5.

Figure 5. Demonstration of autonomy.

2.3.3. Intermarine 600 Full speedboat

The speedboat (Figure 6) has an overall length of 18.6 m and a displacement between 26–30.5 t., a maximum torque of approximately 3,300 N×m (1,300 rpm), and a fuel tank capacity of 2,200 l. It is equipped with two Volvo Penta D13-900 engines (900 HP each = 912.5 CV).


Figure 6. Intermarine 600 Full speedboat.

Diesel tank capacity of 193 l/h, after hybrid conversion 162 l/h, as shown in Figure 7.

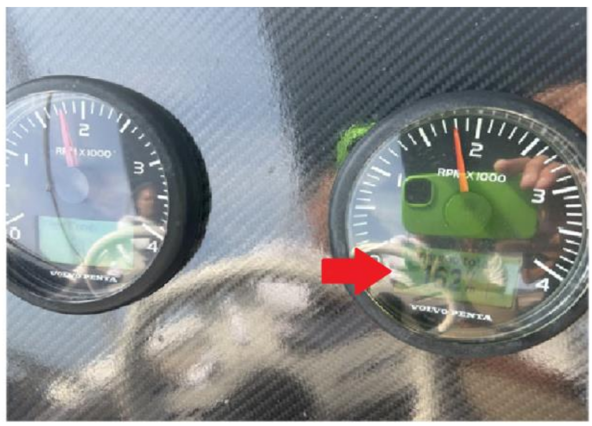

Figure 7. Tank autonomy.

To evaluate the performance of the vessels, Equations 1 to 7 were applied, which allow for the calculation of fuel economy, percentage reduction in consumption, financial savings, and CO_2 reduction, considering the effect of the hydrogen fuel cell compared to the diesel system. The results are described in Table 2 for each boat analyzed.

2.4. Mathematical modeling

2.4.1. Fuel economy per hour (l/h)

The fuel economy in liters/h is obtained when comparing the conventional diesel system with the hybrid system, as shown in Equation 1.

$$E_{l/h} = C_{diesel} - C_{hybrid} \quad (1)$$

Where:

$E_{l/h}$ is the fuel economy per hour [l/h];
C_{diesel} is the hourly fuel consumption in the conventional (diesel) system [l/h];
C_{hybrid} is the hourly fuel consumption in the hybrid system, the consumption after the installation of the hydrogen fuel cell [l/h].

2.4.2. Percentage reduction in fuel consumption ($R_{\%}$)

Calculation of the percentage reduction in fuel consumption when the hybrid system is compared to the diesel system, illustrated in Equation 2.

$$R_{\%} = \frac{C_{diesel} - C_{hybrid}}{C_{diesel}} \cdot 100 \quad (2)$$

2.4.3. Financial savings (US$)

The financial savings of the hybrid system can be determined hourly, monthly, and annually, considering the reduction in fuel consumption produced by the hydrogen fuel cell, as per Equations 3, 4 and 5.

- **Hour:**

$$E_{US\$/h} = E_{l/h} \cdot P\ diesel_{US\$/l} \quad (3)$$

Where:

$P\ diesel$ is the price of diesel in [US$/l].

- **Monthly**:

$$E_{US\$/month} = E_{US\$/h} \cdot \text{Operating hours}_{h/month} \quad (4)$$

- **Annual**:

$$E_{US\$/Year} = E_{US\$/h} \cdot \text{Operating hours}_{h/Year} \quad (5)$$

Where:

$E_{US\$/Year}$ annual financial savings [US$/year];
$E_{US\$/h}$ financial savings per hour [US$/h];
$\text{Operating hours}_{h/month}$ total engine operating [h/month];
$\text{Operating hours}_{h/year}$ total engine operating [h/year].

2.4.4. Carbon dioxide (CO_2) reduction (kg)

The reduction in carbon dioxide emissions due to fuel savings provided by the hybrid system can be calculated on a monthly and annual scale. The diesel emission factor (F_{CO2}) of approximately 2.68 kg CO_2/l [28] is considered, as set out in Equations 6 and 7.

- **Monthly reduction (kg/month):**

$$CO_{2,kg/month} = \text{Savings}_{l/h} \cdot F_{CO2} \cdot H_{month} \quad (6)$$

- **Annual reduction (t/year):**

$$CO_{2,t/year} = \frac{\frac{CO2_{kg} \cdot 12}{monty}}{1000} \quad (7)$$

Where:

$\text{Economy}_{l/h}$ is the diesel savings provided by using the hydrogen fuel cell [l/h];
F_{CO2} is the CO_2 emission factor of diesel [kg of CO_2/l];
H_{month} is the number of operating hours of the boat [month];
$CO2_{t/year}$ is the annual reduction of carbon dioxide [t/year].

2.5. Performance and fuel consumption analysis on the Santos–Paraty route

To analyze the changes resulting from the hybrid conversion, data were collected directly from the boats' monitoring systems, including speed records, travel time, and fuel consumption, ensuring accuracy in the analysis of each propulsion system's performance.

The estimated travel times for each boat are presented in Table 1.

Table 1. Estimated travel times

Speedboat	Speed (kn)	Travel time (h/min)
Ferretti 72ht	24	05:00
Ferretti 660	24	05:00
Intermarine 600 Full	22	05:27

The results of the 120 nautical mile journey, encompassing fuel consumption, operating costs, and CO_2 emissions for the diesel and hybrid systems, are presented in Table 3. The values were obtained using Equations 8 to 13, allowing us to quantify the economic and environmental benefits of hybrid conversion, such as:

- fuel and financial savings;

• percentage reduction in consumption;

• decrease in CO_2 emissions (kg/month and t/year).

2.5.1. Total fuel diesel and hybrid (l/h)

Equation 8 shows the calculation of total fuel consumption during a trip, considering the hourly fuel consumption of the engine and the total navigation time.

$$C_{fuel} = \text{Consumption (l/h)} \cdot \text{Time (h)} \quad (8)$$

Where:

Consumption is the average fuel consumption rate of the engine [l/h];
Time corresponds to the total navigation time [h];
C_{fuel} indicates the total volume of fuel consumed on the journey [l].

2.5.2. Total fuel cost (US$)

This is obtained by multiplying the total volume consumed during operation by the unit price of diesel. Equation 9 expresses this relationship.

$$C_{fuel} = V_{fuel} \cdot P_{diesel} \quad (9)$$

Where:

C_{fuel} is the total fuel cost [US$];
V_{fuel} is the total volume of fuel consumed [l];
$\mathbf{P_{diesel}}$ is the price of diesel [US$/l].

2.5.3. Carbon dioxide (CO_2) emitted (kg)

The amount of carbon dioxide emitted is directly proportional to the volume of fuel consumed. The calculation is performed according to Equation 10. For this calculation, the standard diesel emission factor of 2.68 kg CO_2/l was adopted [28].

$$CO_2 = V_{fuel} \cdot FE_{diesel} \quad (10)$$

Where:

CO_2 is the total mass of carbon dioxide emitted [kg];
V_{fuel} is the total volume of fuel consumed [l];
FE_{diesel} is the diesel emission factor [kg CO_2/l].

2.5.4. Fuel economy (l)

Fuel economy represents the difference between the volume consumed by the diesel system and the volume consumed by the hybrid system. This relationship is expressed by Equation 11.

$$E_{fuel} = V_{diesel} - V_{hybrid} \quad (11)$$

Where:

E_{fuel} is the total fuel economy [l];
V_{diesel} is the total volume of fuel consumed by the conventional system [l];
V_{hybrid} is the total volume of fuel consumed by the hybrid system [l].

2.5.5. Financial savings (US$)

This is the difference between the total fuel cost of the conventional diesel system and the total cost of the hybrid system. This relationship is expressed by Equation 12.

$$E_{fin} = C_{diesel} - C_{hybrid} \quad (12)$$

Where:

E_{fin} is the total financial savings [US$];
C_{diesel} is the total fuel cost of the conventional system [US$];
C_{hybrid} is the total fuel cost of the hybrid system [US$].

2.5.6. Avoided carbon dioxide (kg)

The carbon dioxide avoided represents the reduction in emissions achieved by using the hybrid system compared to the diesel system. This relationship is illustrated by Equation 13.

$$CO_{2,avoided} = CO_{2,diesel} - CO_{2,hybrid} \quad (13)$$

Where:

$CO_{2,avoided}$ is the amount of CO_2 avoided [kg];
$CO_{2,diesel}$ is the total mass of CO_2 emitted by the diesel system [kg];
$CO_{2,hybrid}$ is the total mass of CO_2 emitted by the hybrid system [kg].

2.5.7. Annual carbon dioxide avoided (t/year)

According to Equation 14.

$$CO_{2,year} = \frac{CO_{2,month} \cdot 12}{1000} \quad (14)$$

Where:

$\mathbf{CO_{2,year}}$ is the total amount of carbon dioxide avoided in one year [t/year];
$\mathbf{CO_{2,month}}$ is the amount of CO_2 avoided in one month [kg/month].

2.5.8. Annual carbon value (US$)

A monetary estimate of the damage caused by carbon dioxide emissions was used at US$ 50 per ton [29], illustrated in Equation 19.

$$\mathbf{Carbon_{annual}} = \mathbf{CO_{2,annual}} \cdot \mathbf{Price_{CO2}} \tag{15}$$

Where:

$\mathbf{Carbon_{annual}}$ is the annual economic value associated with CO_2 avoided [US$/year];
$\mathbf{CO_{2,annual}}$ is the amount of carbon dioxide avoided in a one-year period [t/year];
$\mathbf{Price_{CO2}}$ is the reference value per ton of CO_2 avoided [US$/t].

2.6. Costs and evaluations of hydrogen fuel cell systems

The value of each hydrogen fuel cell was US$ 732.50, and three cells were used for each boat, totaling US$ 2,197.50. Therefore, the total cost for the three boats was US$ 6,592.50. The three refills, with an autonomy of 30 hours of continuous operation each, cost US$ 12.57, so for the three boats the cost was US$ 37.71. The equipment installation costs for each boat were US$ 62.84 and for all three US$ 188.52, while the maintenance, projected after ten years, will cost US$ 68.22 for each boat and US$ 204.66 for all three.

Based on these data, the total capex, net capex, opex, and payback were determined, according to Equations 16 to 22.

2.6.1. Total Capex (US$)

Equation 16 is applied to determine this.

$$\text{Capex}_{\text{total}} = \text{C}_{\text{cells,total}} + \text{C}_{\text{inst,total}} \tag{16}$$

Where:

$\mathbf{Capex_{total}}$ is the total initial investment required to implement the system [US$];
$\mathbf{C_{cells,total}}$ is the total cost of the fuel cells used in the project [US$];
$\mathbf{C_{inst,total}}$ is the total cost of installing the cells [US$].

2.6.2. Net Capex (US$)

To determine the net Capex, a useful life of 10 years was considered (Equation 17).

$$\text{Capex}_{\text{liq}} = \frac{\text{Capex}_{\text{total}}}{10} \tag{17}$$

Where:

$\text{Capex}_{\text{liq}}$ is the annualized net Capex [US$/year];
$\text{Capex}_{\text{total}}$ is the total initial investment of the project [US$].

2.6.3. Opex (US$)

Knowing that the annual cost of refilling was US$ 37.71 and the maintenance cost over 10 years was US$ 20.47 per year, Equation 18 was applied to determine the diesel savings.

$$\text{Economy}_{\text{annual,diesel}} = \text{L}_{\text{saved}} \cdot \text{P}_{\text{diesel}} \tag{18}$$

Where:

$\text{Economy}_{\text{annual,diesel}}$ is the annual savings on diesel [US$/year];
L_{saved} is the amount of liters of diesel saved per year [l/year];
P_{diesel} is the price of diesel [US$/l].

2.6.3.1. Value of carbon avoided (US$)

To determine the exact value of carbon avoided, the carbon dioxide avoided per year is first calculated, according to Equation 19.

$$\text{CO}_{2,\text{year}} = \frac{\text{L}_{\text{saved}} \cdot \text{EF}_{\text{diesel}}}{1000} \tag{19}$$

Where:

$\text{CO}_{2,\text{year}}$ is the CO_2 avoided per year [tCO_2/year];
L_{saved} is the amount of liters of diesel saved per year [l/year];
$\text{EF}_{\text{diesel}}$ is the diesel emission factor [$kgCO_2$/l].

Based on the result of Equation 19, the final value of avoided carbon is found (Equation 20).

$$\text{Carbon}_{\text{value}} = \text{CO2}_{\text{an}} \cdot \text{P}_{\text{carbon}} \tag{20}$$

Where:

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$Carbon_{value}$ is the economic value of the emission reduction [US$/year];
$CO2_{an}$ CO_2 avoided per year [t];
P_{carbon} is the price of carbon [US$/t$CO_2$].

2.6.3.2. Annual net operating cost of Opex (US$)

Defined by Equation 21.

$$\Delta\ Opex = (C_{ref} + C_{maint}) - (Economy_{diesel} + Carbon_{value}) \quad (21)$$

Where:

ΔOpex is the variation in annual operating cost [US$/year];
C_{ref} is the annual cost of fuel cell refills [US$/year];
C_{maint} is the annual cost of system maintenance [US$/year];
$Economy_{diesel}$ is the annual diesel savings obtained with the hybrid system [US$/year];
$Carbon_{value}$ is the annual economic value of avoided CO_2 emissions [US$/year].

2.6.4. Payback

Payback is established by Equation 22.

$$Payback = \frac{Capex_{total}}{\Delta\ Opex} \quad (22)$$

3. RESULTS AND DISCUSSION

The evaluation of the energy performance of the boats after the installation of the hydrogen fuel cell showed significant gains in efficiency and sustainability, as presented in Tables 2 and 3.

Fuel consumption, as shown in Table 2, was significantly reduced in all boats analyzed.

The Ferretti 72ht, with a diesel consumption of 123 l/h, achieved a saving of 10 l/h after the installation of the hydrogen fuel cell, representing a reduction of 8.13% and a financial saving of US$ 15.97 per hour. The Ferretti 660, which consumed 162 l/h of diesel, showed a reduction of 10.49%, reducing its consumption to 145 l/h with the fuel cell, a saving of 17 l/h, and a saving of US$ 27.16 per hour. Finally, the Intermarine 600 Full, which reduced its consumption from 193 l/h to 162 l/h, generating a saving of 31 l/h, achieved a 16.06% reduction in consumption and a gain of US$ 49.53 per hour.

Table 3 shows, in economic and environmental terms, the benefits of installing a hydrogen fuel cell. Achieving monthly savings of US$ 3,834.82 and annual savings of US$ 46,017.84, the Ferretti 72ht avoided emitting 6,432 kg of CO_2 per month, equivalent to 77.18 tons annually. The Ferretti 660 achieved monthly savings of US$ 6,519.21 and annual savings of US$ 78,230.52, in addition to avoiding the emission of 10,934.40 kg of CO_2 per month, or 131.21 tons annually. Due to its larger size, the Intermarine 600 Full achieved a monthly carbon dioxide reduction of 19,939.20 kg, which corresponds to 239.27 tons per year, resulting in monthly financial savings of US$ 11,887.97 and annual savings of US$ 142,655.64. The total annual savings from the three boats was US$ 266,904.00, while the annual gains from reduced carbon dioxide emissions amounted to 447.66 tons of CO_2.

Therefore, the results show that the environmental gains from reducing carbon dioxide emissions were as significant as the reduction in fuel consumption. Thus, conversion using hydrogen fuel cells proved to be efficient, economically advantageous, and environmentally sustainable.

The analysis of navigation data on the route between Santos (SP) and Paraty (RJ) resulted in operational data, presented in Table 4, showing speed, time, and consumption. Table 5 presents the comparative costs between the diesel and hybrid systems, fuel reductions, and financial

Table 2. Fuel consumption and economy

Speedboat	Original consumption (l/h)	Fuel consumption with fuel cell (l/h)	Economy (l/h)	Reduction (%)	Economy (US$/h)
Ferretti 72ht	123	113	10	8,13	15,97
Ferretti 660	162	145	17	10,49	27,16
Intermarine 600 Full	193	162	31	16,06	49,53

savings, and Table 6 shows the reduction in carbon dioxide emissions.

the Ferretti 660 shows a reduction from US$ 1,294.25 to US$ 1,158.43, a difference of US$ 135.81.

Table 3. Economic and environmental benefits

Speedboat	Monthly savings (US$/month)	Annual savings (US$/year)	CO2 saved (kg/month)	CO2 saved (t/year)
Ferretti 72ht	3.834,82	46.017,84	6.432,00	77,18
Ferretti 660	6.519,21	78.230,52	10.934,40	131,21
Intermarine 600 Full	11.887,97	142.655,64	19.939,20	239,27
TOTAL	22.242,00	266.904,00	37.305,60	447,66

In Table 4, the travel time was calculated based on cruising speeds, being 24 knots for the Ferretti 72ht and Ferretti 660 and 22 knots for the Intermarine 600 Full, while the estimated travel time for each vessel was 5 hours for the Ferretti 72ht and Ferretti 660, and 5.5 hours for the Intermarine 600 Full. It is important to note that even with the installation of the hydrogen fuel cell, there is no change in cruising speed; therefore, the travel time remains the same for both diesel and hybrid systems. Thus, the analysis between the systems focused exclusively on fuel economy, operational costs, and reduction of carbon dioxide emissions. The results showed that for the Ferretti 72ht, the total fuel consumption on the journey, after the installation of the fuel cell, was reduced from 615 l to 565 l. For the Ferretti 660, there was a reduction in consumption from 810 l to 725 l. The vessel with the highest fuel consumption was the Intermarine 600 Full, which reduced its consumption from 1,053 liters to 884 liters. The three boats analyzed showed a total saving of 304 liters after the conversion.

The greatest savings appear in the Intermarine 600 Full, with a saving of 169 liters, where the cost decreases from US$ 1,682.09 to US$ 1,411.91, indicating a difference of US$ 270.18. In total, the cost of operating diesel for the three vessels was US$ 3,959.01. With the hybrid system, this total decreases to US$ 3,473.12, resulting in savings of US$ 485.89. These results demonstrate the viability of hybrid technology, which shows a significant reduction in operating costs.

The results of the carbon dioxide (CO_2) emission reductions are presented in Table 6. By avoiding 134 kg of CO_2, the Ferretti 72ht boat showed that emissions decreased from 1,648.20 kg to 1,514.20 kg. The Ferretti 660 showed a reduction from 2,170.80 kg to 1,943.00 kg, representing 228 kg of CO_2 avoided. The Intermarine 600 Full showed the greatest difference, as its emissions reduced from 2,821.31 kg to 2,368.15 kg, resulting in 453 kg less CO_2 in the atmosphere. In the sum of the results of the three vessels, emissions fell from 6,640.31 kg to 5,825.35 kg, equivalent to 815 kg of CO_2 avoided.

Table 4. Operational data

Speedboat	V (kn)	T (h)	Diesel consumption (l/h)	Total diesel (l)	Hybrid consumption (l/h)	Total hybrid (l)
Ferretti 72ht	24	5	123	615	113	565
Ferretti 660	24	5	162	810	145	725
Intermarine 600 Full	22	5,5	193	1.053	162	884
TOTAL	—	—	478	2.478	420	2.174

Table 5 shows a comparison between operating costs using diesel and costs after the installation of the hydrogen fuel cell in the three vessels. For the Ferretti 72ht, with a saving of 50 liters, the cost decreased from US$ 982.67 to US$ 902.78, a gain of US$ 79.89. For the 85 liters saved,

To determine the tons of carbon dioxide avoided annually, according to Equation 14, we obtain a result of 9.78 t/CO_2/year. Based on this result, the annual carbon

Table 5. Costs (diesel vs hybrid)				
Speedboat	**Diesel cost (US$)**	**Hybrid cost (US$)**	**Economy (US$)**	**Economy (l)**
Ferretti 72ht	982,67	902,78	79,89	50
Ferretti 660	1.294,25	1.158,43	135,81	85
Intermarine 600 Full	1.682,09	1.411,91	270,18	169
Total	3.958,01	3.473,12	485,88	304

value, as shown in Equation 15, can be established as US$ 488.99.

Table 6. Reductions carbon dioxide			
Speedboat	**Diesel carbon dioxide (kg)**	**Hybrid carbon dioxide (kg)**	**Carbon dioxide avoided (kg)**
Ferretti 72ht	1.648,20	1.514,20	134
Ferretti 660	2.170,80	1.943,00	228
Intermarine 600 Full	2.821,31	2.368,15	453
Total	6.640,31	5.825,35	815

Table 7 presents the economic results of the hydrogen fuel cells in the three boats studied, referring to Equations 16 to 22.

To analyze the initial investment, the value of the cells, which was US$ 6,592.50, is added to the installation cost of US$ 188.52, totaling US$ 6,781.02 (total Capex). Considering the equipment's useful life as 10 years, the net Capex was used to define the annual value, resulting in US$ 678.10.

The Opex costs show the expense with refills of US$ 37.71, the annual maintenance cost which was US$ 20.47 for ten years, and the reduction in diesel consumption which obtained a return of US$ 486.40 annually.

Also, the environmental benefit was shown, through the reduction of carbon dioxide emissions, where the annual value of carbon generated a benefit of US$ 40.74 per year. All these values combined determined the annual net operating cost of Opex resulting in a value of US$ - 468.96/year. The negative result occurs because the

Table 7. Economic results	
Item	**Value (US$)**
Total Capex	6.781,02
Net Capex (10 years)	678,10 /year
Annual refill	37,71
Annual maintenance	20,47
Annual diesel savings	486,40/year
Carbon credit value	US$ 40.74 /year
Net annual OPEX	– 468,96/year
Payback	14,5 years

annual savings generated by the system are greater than its operating costs, thus indicating a gain and not a loss.

The payback period, Payback, which was 14.5 years, showed the viability of installing hydrogen fuel cells on the three boats.

4. CONCLUSION

In the pursuit of environmental sustainability associated with the use of clean energy, this study, with the objective of implementing more efficient systems, analyzed the conversion of three motorboats, Ferretti 72ht, Ferretti 660, and Intermarine 600 Full, with diesel propulsion systems, to hybrid configurations with hydrogen fuel cells. The results obtained showed that after the installation of the hydrogen fuel cells, there were fuel savings, with the boats consuming 8% to 16% less diesel, showing a reduction of 10 to 31 liters per hour. Economically, this reduction represented US$ 49.53 saved per hour of use, providing an annual gain of US$ 266,904.00. Due to this saving, the amount of CO_2 that was no longer emitted was 447.66 tons per year.

The resulting data from the route between Santos (SP) and Paraty (RJ) showed that the total diesel used decreased from 2,478 liters to 2,174 liters, generating savings of 304 liters per trip for the three vessels, and when comparing the cost of diesel with that of the hybrid system, there was a profit of US$ 485.88. These savings were reflected in the environmental reduction, with the hybrid system avoiding the emission of 815 kg of carbon dioxide. With an initial investment of US$ 6,781.02 and having an estimated useful life of 10 years, the result is an annual net Capex of US$ 678.10.

The operating costs of the system are not high, presenting refill costs of US$ 37.71, annual maintenance of US$ 20.47, and annual savings on diesel of US$ 486.40, in addition to US$ 40.74 per year in carbon credits. As a result, net annual Opex was negative US$ - 468.96. The payback period was estimated at 14.5 years. Finally, the data confirms that hydrogen fuel cells improve the performance of motorboats, reduce diesel consumption, lower costs, and prevent carbon dioxide emissions into the atmosphere, making the technology a promising alternative for the nautical sector, contributing to cleaner, more efficient maritime transport aligned with global carbon neutrality goals.

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