Electric Mobility Study Using Digital Twin for an Electric Boat: Case Study of UFPA Poraquê Boat

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***Abstract*— The present work aims to develop a numerical model of a real solar boat system that will be implemented in UFPA, as part of the SIMA project. The MATLAB/Simulink modeling software was used in conjunction with PVSyst to obtain electric and physical operating parameters of the boat. Additionally, it is possible to perform an ecological and economic analysis of the boat, comparing similar models but with traditional internal combustion technology. The results demonstrate the simulated components, as well as the economic advantage in terms of fuel cost and reduced CO_2 emissions.**

Keywords*— *Electric Mobility, Electric Solar Boat, Photovoltaic Systems, Digital Twin.

I. INTRODUCTION

The energy transition is a global trend due to the increase in world energy consumption, whether in residential loads, industries, and especially in transportation. Concerns about the limitation of non-renewable sources, high pollution levels, and various other negative impacts make this transition increasingly urgent.

This scenario forces researchers to increase the use of renewable energy resources as a substitute for fossil fuel-based technologies. Ships, as one of the most important modes of transportation in the world, also require diesel oil, used as fuel in the main propulsion systems and generators that supply electrical needs. Solar energy has been considered as the most suitable renewable energy source (RES) to replace the role of fuel in ships [1]. According to data from the National Energy Balance - BEN for the year 2022, the internal energy supply (total energy available in the country) reached 301.5 Mtoe (Million tons of oil equivalent), registering an increase of 4.5% compared to the previous year, and the trend is that these values will continue to increase. The same BEN report shows that 32.5% of this energy was allocated to the transportation sector, which is also the sector with the smallest share of its renewable energy source, only 23% [2].

Therefore, alternatives that promote electric mobility are essential to meet such demand more responsibly. Another motivator for this work is the great potential of Brazil's geographical characteristics for the waterway mode. Brazil has a fluvial network of 63,000 km in length, with almost 27,000 km of navigable rivers and 15,000 km of navigable routes, however, it uses only 30% of its entire river network for the commercial transportation of goods and passengers [3]. Currently, solar boats are defined as vessels that use an electric motor powered by electrical energy from the conversion of solar energy by photovoltaic modules, which are alternatives to the need for cleaner and more ecological water transport.

The use of photovoltaic systems in boats is a means of generating electrical energy over water without using combustion engines. The photovoltaic modules convert energy silently, and unlike wind turbines, they do not have rotating components that can affect the stability of the boat [1]. Another way to classify vessels is by their shape, whether they are monohulls, catamarans, or trimarans [4]. According to the work of [1], the best possible method for using solar energy in boats is to use catamarans with a flat roof and a structure with better use of area to allocate the photovoltaic modules, and they receive maximum solar radiation since the sun's rays reach the plates without obstacles from the structure of the boat itself.

II. METHODOLOGY

A. MATLAB/Simulink

MATLAB is a software used to perform various mathematical procedures, integrating numerical analysis, matrix calculations, signal processing, and graph plotting. The software uses a programming language similar to Fortran, Basic, or C programming language [5].

MATLAB also has various resources that facilitate the simulation of power systems, allowing modeling and analysis of dynamic systems. One of the features is Simulink, which is integrated with MATLAB and uses a graphical interface, where it is possible to use blocks already present in the software library, as well as include custom blocks [6]. In Fig. 1, an example of a control system for a helicopter using Simulink is shown.

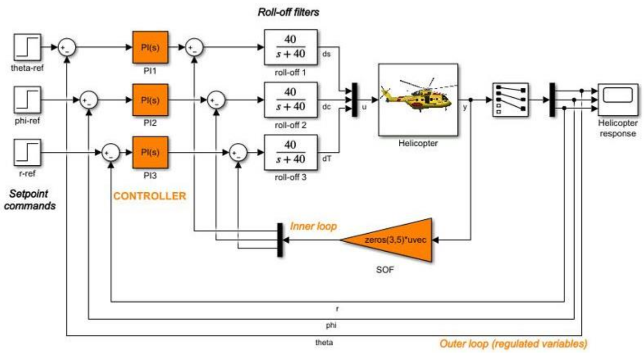

Fig. 1. Example of a control system in Simulink.

In addition, there are also specific libraries such as Simscape, which is used for power electronics, making it easy to simulate photovoltaic modules, allowing for the use of basic elements up to the construction of a complete physical system [7].

Finally, MATLAB also has the ability to create Digital Twins, which represent a way to evaluate, simulate, and improve products. It is possible to virtually replicate a real physical system, so that the digital model can provide important data on the stability and use of the product, such as the product's life cycle in analysis [8].

B. *PVSyst*

PVSyst is a photovoltaic system simulation software that has a large database of meteorological, photovoltaic module, inverter, and energy storage system specifications. It also allows the addition of technical parameters for equipment not present in the software. To perform the simulation, input data is entered, demonstrating the location and the generation system used, and finally, a report with graphs, tables, and photovoltaic generation values is presented. The main simulation variables are: meteorological data; inverter losses; energy use; system efficiency; and performance ratio [9].

All simulation factors consider the location, as there is variation in solar radiation. This difference in position is observed in the form of a set of parameters such as latitude, longitude, and altitude of a location [11].

III. SUBJECT OF STUDY: SIMA PROJECT.

The Sistema Inteligente Multimodal da Amazônia (SIMA) Project is an initiative of the Universidade Federal do Pará (UFPA) in partnership with Norte Energia and the Center for Research and Development in Telecommunications (CPqD). It consists of the following modes: electric buses and electric boats, with a photovoltaic generation structure, storage system, and charging stations for electric vehicles, with the Guamá campus of the Universidade Federal do Pará being the pilot of the project [10].

A. *Solar Electric Boat*

The SIMA project includes the implementation of electric buses, which are already in full operation on the UFPA campus. There is also a plan to use a solar electric boat. The present study presents a catamaran-type boat, in which there will be a photovoltaic system in conjunction with a storage system. Table I presents the physical specifications of the electric boat such as length, width, and weight of the structure.

TABLE I - PHYSICAL SPECIFICATIONS OF THE BOAT.

Specifications	Value
Length	12,3 m
Width	6 m
Weight of the structure	1386 kg

Table II presents various characteristics of the propulsion system of the electric boat, such as information about the motor, power, and technical details.

TABLE II- SPECIFICATIONS OF THE PROPULSION SYSTEM.

Parameters	Value
Quantity of motors	2
Maximum mechanical power (kW)	24
Nominal voltage (V)	51
Total weight (kg)	118

Table III presents parameters of the photovoltaic system and storage system, such as power, quantity, weight, and other parameters.

TABLE III- SPECIFICATIONS OF THE PHOTOVOLTAIC AND STORAGE SYSTEM.

Parameters	Valor
Maximum PV power	6,7 kWp
Quantity of PV modules	20
Technology of PV modules	Polycrystalline
Weight of PV system	430 kg
Total capacity of storage system	615 Ah
Quantity of batteries	72
Weight of storage system	438 kg
Battery technology	lithium ion

IV. RESULTS

A. *MATLAB/Simulink*

The model generated in MATLAB software with Simulink tool and using the Simscape library resulted in a simplified block diagram of the operation of the solar electric boat, considering the use of mechanical, electrical, and physical components in the simulation. Fig. 2 presents the simplified diagram.

a) Photovoltaic Modules

To simulate the arrangements of photovoltaic modules, the PVarray block from the Simscape library was used, which has two parameter inputs, which are: irradiation and temperature; in addition to the two inputs, the block has three outputs, one negative pole and one positive pole, for voltage measurements, and another output called "m", which shows the measured parameters. Fig. 2 shows the block representing the solar generation system.

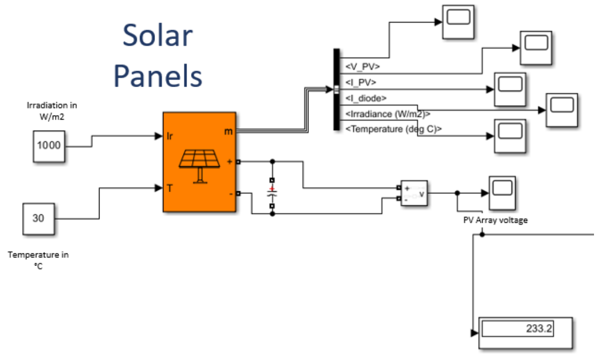

Fig. 2. PVarray block.

Fig. 3 shows the curve of current and power as a function of voltage for scenarios of different ambient temperatures, with 25ºC and 45ºC being presented.

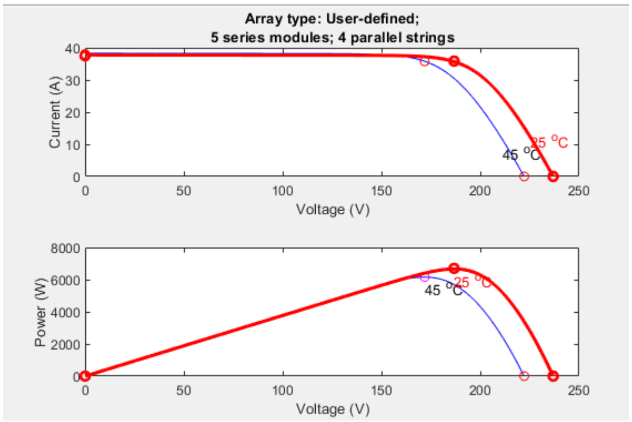

Fig. 3. Current and power curves as a function of voltage for temperatures of 25ºC and 45ºC.

For the case defined in the schematic input, with irradiance of 1000W/m2 and 30°C temperature, the simulation defines that the voltage output has a value of 233.2V, as shown in Fig. 4.

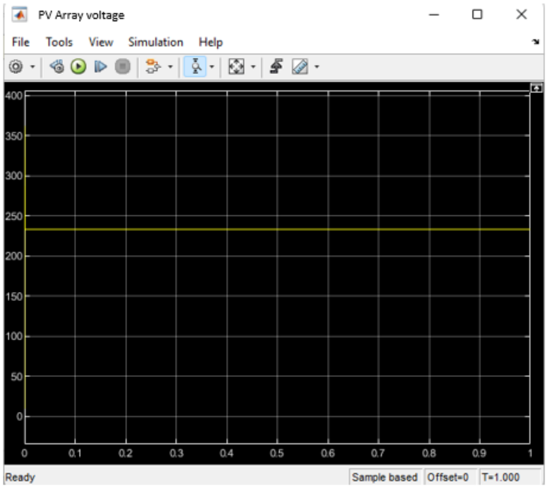

Fig. 4. Output voltage of the photovoltaic system.

The battery bank charging voltage is 72V, which is lower than the PV array output voltage. Therefore, it is necessary to use a device to decrease the output voltage to match the input voltage of the battery bank. Hence, a DC-DC converter is of utmost importance.

b) DC-DC Converter

The DC-DC converter is important for photovoltaic systems in various situations, from reaching the maximum power point of generation through MPPT to reaching the ideal voltage range for charging the storage system. The converter used is intended to regulate the voltage to 72 V, thus making the photovoltaic system compatible with the storage system. Fig. 5. shows the model in Simulink. Fig. 6 shows the output result of the photovoltaic system voltage.

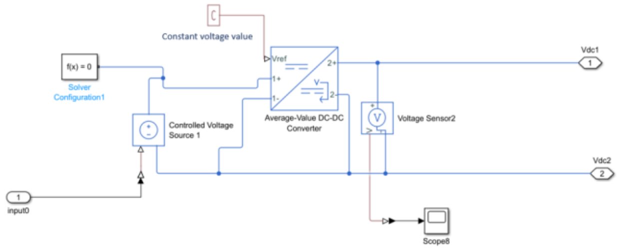

Fig. 5. DC-DC converter in Simulink.

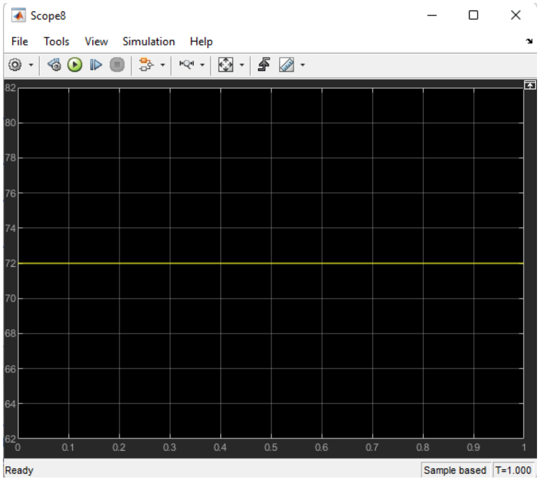

Fig. 6. DC-DC converter output voltage.

c) Battery bank

For the representation of the storage system, the Simscape Battery block was used, as shown in Fig. 7, with three blocks connected in parallel with the parameters described in Fig. 8, where the main parameters are 76.8 V nominal voltage, 205 Ah capacity, which with the three blocks composes the total of 615 Ah of the storage system.

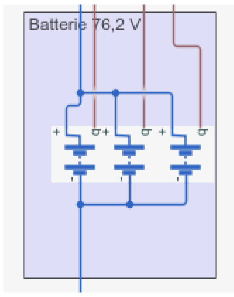

Fig. 7. Battery bank represented in Simulink.

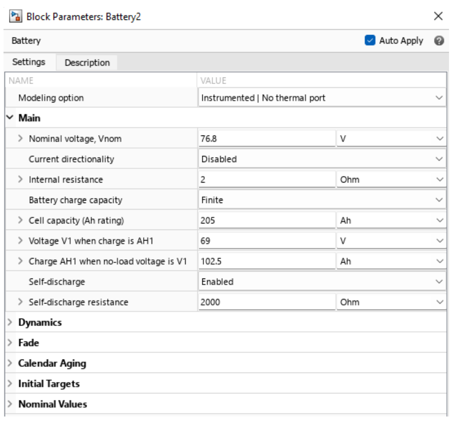

Fig. 8. Storage system parameters.

The parameters V1 Voltage and AH1 Charge represent the no-load voltage and no-load capacity at a specific point, which are used to plot the battery discharge curve, as shown in Fig. 9.

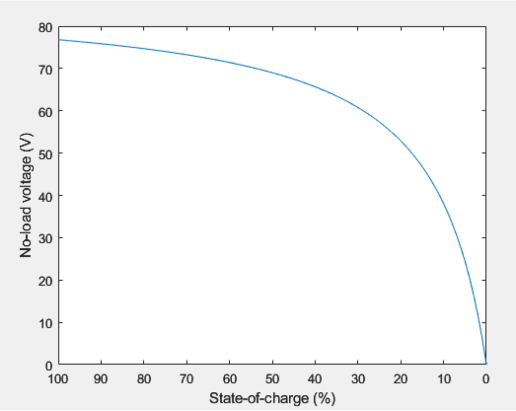

Fig. 9. Storage system discharge curve.

d) DC-AC Converter

The DC-AC inverter is one of the most important components of the system because it converts the voltage in the DC bus, where the photovoltaic generator and the storage system are connected, into alternating current at the operating specifications of the electric motors. In the original design, two inverters are used to divide the power, while in the simulation only one block of the Average-Value Inverter (Three-phase) was used to perform the entire conversion process. In Fig. 10., we can see the block image with the positive and negative DC inputs and the three-phase AC output on phases ABC.

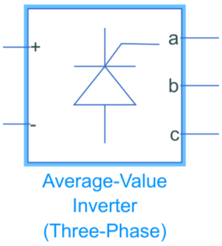

Fig. 10. Electric Inverter Block.

The parameter configurations for the block were chosen according to the motor specifications, which are three-phase at 60 Hz, 120º phase shift, and an output voltage of 51 V, as shown in Fig. 11.

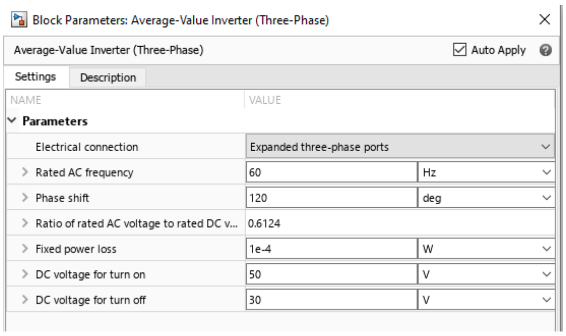

Fig. 11. Inverter block parameters.

Thus, the energy signal at the output of the inverter is shown in Fig. 12., with maximum voltage values of 53 V and frequency of 60 Hz.

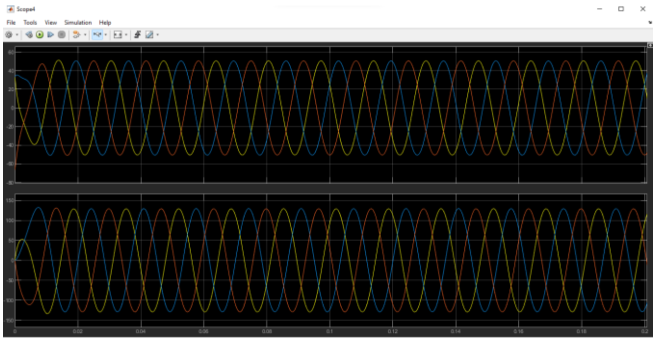

Fig. 12. Graph of voltage and current at the inverter output.

e) Motors

Thus, to model the propulsion motors of the boat, the Induction Machine Squirrel Cage block was used, which represents a squirrel cage three-phase motor. As can be seen in Fig. 13, two motors connected in delta were used just after the frequency inverter. This block has two outputs R, which is the mechanical rotational port associated with the machine rotor, which transmits the values of angular speed and output torque of the motor.

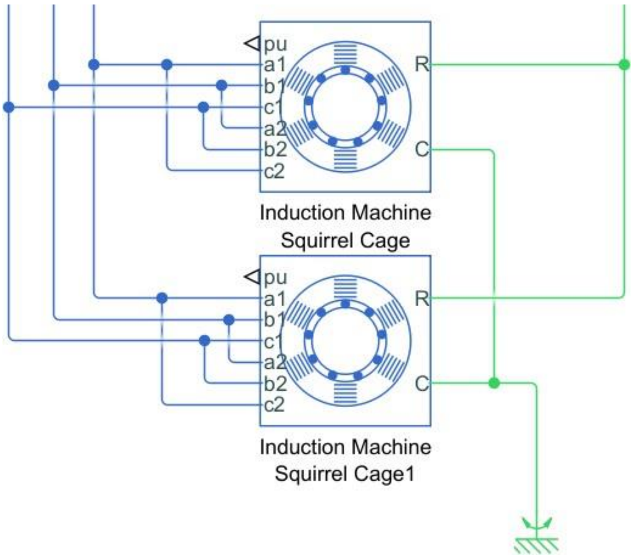

Fig. 13. Blocks of three-phase motors for boat propulsion.

The design parameters were added to the simulation for each motor with 13kW of power and a nominal voltage of 51 V in three-phase alternating current and a frequency of 60 Hz, as shown in Fig. 14.

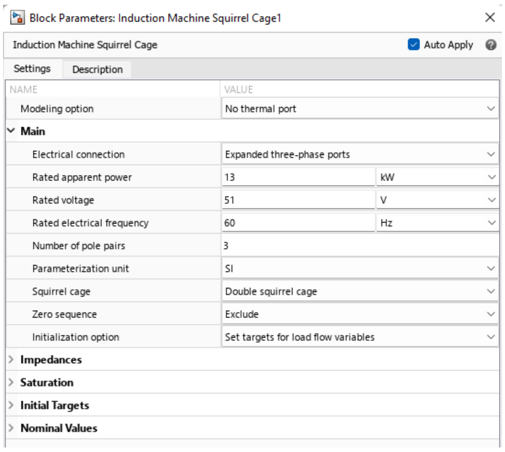

Fig. 14. Parameters of the Induction Machine block.

f) AC-DC Converter

As the photovoltaic generation system does not supply all the energy needed for the boat's daily autonomy, a power supply for recharging on land at the charging stations is necessary. Thus, an AC-DC converter was developed to transform the 220 V AC from the UFPA power grid to the continuous 72 V DC required for the battery bank. For this, a Subsystem was developed in Simulink with an alternative voltage source to represent the energy input, a switching controlled by a Step block to indicate when it is on or off, and the AC-DC converter power source subsystem, as shown in Fig. 15.

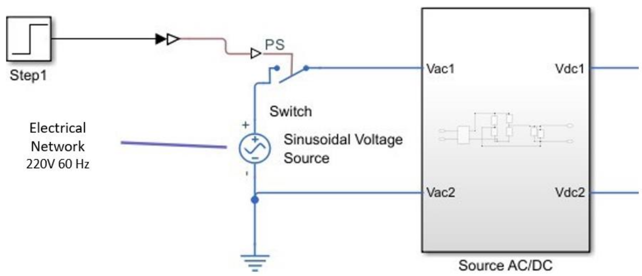

Fig. 15. AC-DC Converter Subsystem.

The converter source diagram was built based on a simple analog electronics circuit, with a voltage transformer, a rectifying bridge with diodes, and a capacitor. This circuit allows only unilateral conversion of the alternating current from the university grid into direct current for battery charging. The source circuit is shown in Fig. 16.

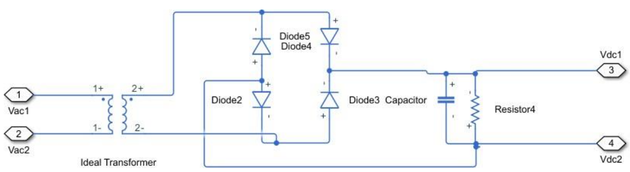

Fig. 16. AC-DC converter source.

g) Physical Representation of the Boat

The physical part of the boat was represented just after the motors, and it has three measurement blocks and four blocks for system representation. The first three are the angular velocity meter at the output of the motors (the measurement at its output is in rad/s, so a constant block was used to convert it to rpm), the force meter that shows the projected force on the boat (in Newtons), and the linear velocity meter that shows the cruise speed of the boat itself (with unit in m/s, so a converter was used to have the values in Knots).

The second part includes the gearbox block to increase torque and propulsion, the Wheel and Axle block that converts wheel and axle size, along with the angular rotation speed and torque data to produce a propulsion output force in the boat. Subsequently, there are two blocks that represent the boat's inertia with data on its mass, calculated as 1,389 kg plus 20 passengers with an average weight of 70 kg, resulting in a total of 2,789 kg. Additionally, there is a block that simulates the friction force between the boat and the water of 150 N/(m/s). The complete system is shown in Fig. 17.

From these sensors it was possible to assemble different scenarios to evaluate the operation of the boat. Fig. 18. shows the result of a simulation at full power lasting 100 seconds in which the boat consumed the maximum design speed of 10 knots in 40 seconds.

Another simulation using the total autonomy time predicted by design of 3 hours and 5 minutes, totaling 11,100 seconds, was carried out at cruising speed and the model achieved the expected result, maintaining its speed throughout the autonomy period, however, considering the constant value of irradiation at 1,000 W/m2. As can be seen in the graph of Fig. 19.

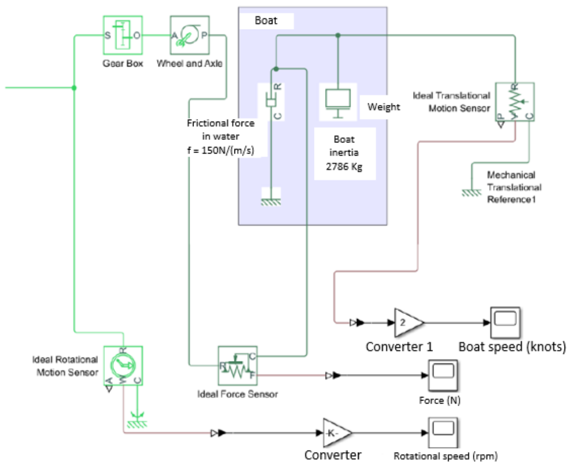

Fig. 17. System for representing the physical parameters of the boat.

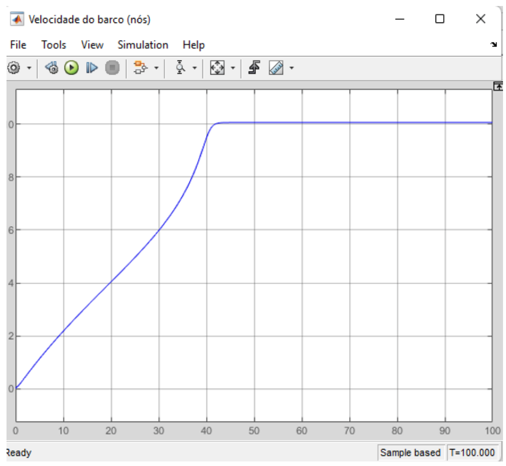

Fig. 18. Graph of Boat Speed in Knots.

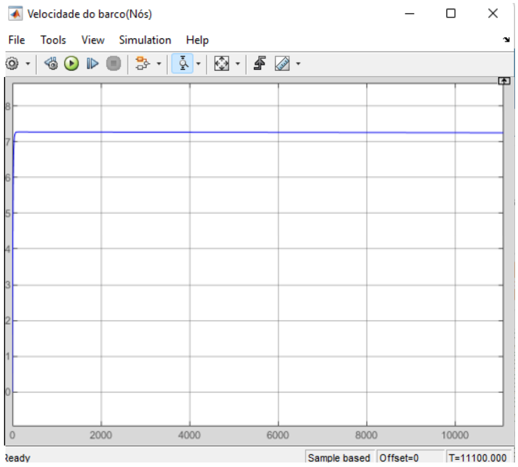

Fig. 19. Graph boat speed in knots for full range.

B. Financial and Ecological Comparasion

A comparison between the financial operating cost of this solar boat and a similar boat with internal combustion was carried out. Firstly, an estimate of the total energy consumption of the solar boat on a normal sunny day was made. Using the values of installed peak power Pp, the average PVOUT, based on the specific production calculated by PVSYST of 4.21 kWh/kWp/day (annual average value), which considers the losses in the system. Table IV presents the energy generation of the photovoltaic system.

TABLE IV - DAILY ENERGY GENERATED BY THE PHOTOVOLTAIC SYSTEM.

PVOut (kWh/kWp)	P(kWp)	$E_{modules}$ (kWh)
4.21	6.7	28.20

With these generation values, it is possible to calculate the total energy available in a day of service shown by (1). The Total Energy (E_{total}) is the sum of the energies from the modules ($E_{modules}$) and the storage system ($E_{batteries}$).

$$E_{total} = (E_{modules} + E_{batteries}) \quad (1)$$

The energy generated by the modules is 28,207 kWh and the energy available in the storage system is 47,23 kWh. So, we have that the total energy is 75,437 kWh.

Subsequently, the energy expenditure in the propulsion system was calculated from the engine load and its percentage of use to maintain the cruising speed, shown in (2). Total consumption (C_{total}) is the ratio between the engine power (P_{engine}), the number of engines (n) and the percentage of engine utilization at cruising speed (Pu).

$$C_{total} = P_{engine} * A * n * Pu \quad (2)$$

Where:

$P_{engine} = 13.38$ kW.
Pu = 89%.
A = 3.08 h.
n = 2.

When the calculations are carried out, the value of 73.35 kWh is obtained. In this way, it can be seen that for the specified values of storage and generation of the boat, they are sufficient for the proposed autonomy, since $Etotal$ is greater than C_{total}, and it has a total coverage rate of daily consumption with its photovoltaic generation system of 38%, C_{total}/E_{total}. The other 62% of the battery charge will be recharged by the University's charging stations.

Based on these results, it was possible to calculate the daily and monthly cost of electricity coming from the electrical network for the catamaran, based on the different types of tariffs, namely the commercial tariff, the green tariff modality at the tip (Green NP) and the green tariff modality outside tip (Green FP) as shown in Table V, obtained through the local energy concessionaire in the year 2022.

TABLE V - DAILY COST OF BOAT ELECTRICITY.

Fare Type	Price (BRL/kWh)	Grid Energy (kWh)	Daily energy cost	Energy cost per month
Commercial	R$ 0.88	45.15	R$ 39.68	R$ 1190.54
Green NP	R$ 3.59	45.15	R$ 162.13	R$ 4863.88
Green FP	R$ 0.33	45.15	R$ 14.74	R$ 442.22

Based on data from a catamaran boat with a cruising speed of 8 knots (close to 7.3 knots for a solar boat), a consumption of 20 liters per operating hour is estimated. In this way, the consumption was calculated for the same autonomy of 3 hours and 5 minutes and the cost of fuel, considering the average value of nautical diesel for the year 2022, being demonstrated in (3).

$$C_{Dtotal} = (C_{D/h} * A) \quad (3)$$

Where C_{Dtotal} is diesel consumption in liters and CD/h is diesel consumption per hours of operation. Carrying out the calculations made from (3) the value of 61.6 liters is obtained.

In this way, it was possible to calculate the daily cost of fuel only, using the average price of diesel in 2022. The result is shown in Table V, and it can be seen that it is more than 10 times higher than the cost of electricity for the solar boat.

TABLE V- COST AND CONSUMPTION OF DIESEL.

total daily consumption (l)	Diesel Price (BRL/l)	Diesel daily cost (BRL)	Diesel monthly cost (BRL)
61.6	R$ 6.77	R$ 417.03	R$ 12,510.96

Diesel-powered vehicles emit more CO2 per unit volume or weight of fuel compared to other motorized modes. In this work, an average emission factor of 2.6 kg of CO2 was used for each liter of diesel burned in combustion, which added to the average value of 0.5 kg of CO2 emitted to produce and distribute the fuel, we arrived at at a total emission rate of around 3.2 kg of CO2 per 1 liter of diesel. Through (4) calculates the total daily emission of CO2.

$$E_{tCO2} = (E_{pCO2} + E_{qCO2}) * Vd \quad (4)$$

Where E_{tCO2} is the total CO2 emission in the atmosphere, E_{pCO2} the CO2 emission in the production of 1l of diesel and E_{qco2} the burning of 1l of Diesel, and finally, Vd the daily volume of diesel, thus totaling 197,12 kg/day.

With this daily emission value and considering that the source of electricity generation comes from non-polluting renewable technology, it is possible to calculate the number of tons of CO2 that are not released into the atmosphere annually. Therefore, the annual value of CO2 emissions is 71,948.8 kg/year.

Almost 72 tons of pollutants per year. The contribution of a modal like this to the environment is evident. Maintenance costs are much lower and return on investment can be even faster if you use an off-peak charging strategy.

V. CONCLUSION

Electric mobility is a worldwide trend and necessity. Electric and solar boats are a promising alternative for the electrification of transportation and reduction of carbon emissions, as they rely on renewable sources of energy. This is especially relevant in the Amazon region, where water transportation is widely used. The future of electric mobility relies on constant simulations and digital experiments, where digital twins enable more accurate performance prediction and preventive maintenance through data monitoring.

In this context, the present study analyzes the system of a solar boat from the SIMA project, which will be implemented at UFPA with the aid of MATLAB software. The system modeling was done using Simulink tool. The operational parameters of the electrical system were studied, obtaining results that demonstrate the electrical and physical application, considering final operation aspects such as module voltage, voltage with converters, displacement speed, and other results obtained through simulation.

The data obtained on the operation of the solar boat and its comparison with a similar internal combustion model demonstrate that the operating cost is much lower in a solar boat, considering the high diesel consumption and its higher price compared to electricity. Another beneficial point is the reduction of environmental impact, since the Brazilian electric matrix is mostly composed of renewable sources, and UFPA's network still has several photovoltaic systems connected to the grid, as a result of the success of the SIMA project, which saves almost 72 tons of CO2 in the atmosphere, avoiding a considerable impact. Therefore, projects like SIMA should be replicated in cities worldwide to seek greater sustainability.

Regarding the simulation part, it was concluded that the system monitoring through digital simulation is efficient, as its results confirmed the project parameters. Therefore, future works involving this digital twin theme deserve attention and can contribute even more to advances in electric mobility research.

ACKNOWLEDGEMENTS

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