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Article

Use of Distributed Energy Resources Integrated with the Electric Grid in the Amazon: A Case Study of the Universidade Federal do Pará Poraquê Electric Boat Using a Digital Twin †

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Abstract: Electric mobility is a global trend and necessity, with electric and solar boats offering a promising alternative for transportation electrification and carbon emission reduction, especially in the Amazon region. This study analyzes the system of a solar boat from an electric mobility project—to be implemented at Universidade Federal do Pará (UFPA)—using MATLAB software for modeling. The Simulink tool was utilized to model the system, focusing on operational parameters such as module voltage, converter voltage, and speed. The results indicate that the solar boat's operational cost is significantly lower compared to a similar internal combustion model, considering diesel's high consumption and cost. The environmental impact is also reduced, with nearly 72 tons of CO_2 emissions avoided annually, thanks to Brazil's renewable energy matrix. Simulations confirmed the project's parameters, demonstrating the efficiency of digital-twin technology in monitoring and predicting system performance. The study underscores the importance of digital twins and renewable energy in promoting sustainable transportation solutions, advocating for the replication of such projects globally. Future research should focus on further advancing digital-twin applications in electric mobility to enhance predictive maintenance and operational efficiency.

Keywords: electric mobility; solar boats; digital twin; renewable energy; carbon emission reduction; sustainable transportation

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1. Introduction

The energy transition and the decarbonization of vehicles are global trends driven by the increasing consumption of electricity, especially in transportation, and the urgent need to reduce greenhouse gas (GHG) emissions [1]. This context has bolstered the growth of distributed generation, including photovoltaic and storage systems, aimed at more intelligently and sustainably meeting the complex energy needs of urban centers [2].

In 2022, the transportation sector accounted for 31% of the final energy consumption in Europe [3], and in 2023, this percentage was 33% in Brazil [4]. These data highlight the significant participation of the transport sector in the global energy matrix. However, the transition from fossil fuels to non-fossil electricity depends on each country's electricity matrix composition, increasingly focused on clean and renewable energy generation to reduce GHG emissions [5]. In this context, replacing internal combustion vehicles is crucial, as they are one of the main GHG emitters [6]. It is important to note that while vehicles significantly contribute to GHG emissions, the effectiveness of this replacement depends on each country's electrical matrix, many of which still rely on fossil fuels for electricity generation [4,7].

In the Brazilian context, diesel and gasoline represent 71.1% of transport energy consumption, while 22.5% comes from renewable sources such as biodiesel and ethanol. Brazil stands out as a pioneer in decarbonizing primary energy sources, with one of the cleanest energy and electricity matrices globally, with approximately 89% renewable sources in the electricity matrix, compared to 35% in OECD countries and the global average of 30% [4]. The Brazilian transport sector has 22.5% of its energy consumption from renewable sources [4].

When addressing mobility in Brazil, it is crucial to take into account river transport. River mobility plays a vital role in the country, which features a river network spanning 63,000 km, with nearly 27,000 km deemed navigable. Nevertheless, only about 30% of this network is utilized for the commercial transportation of goods and passengers [8]. To address this demand in a more sustainable manner, alternatives that promote electric mobility are essential.

In addition to advancements in technologies for land transportation, such as electric cars and buses, it is essential to promote research and development for water-based transport modes. A notable example in the Amazon is the Intelligent Multimodal System of the Amazon (SIMA), hosted at the Universidade Federal do Pará (UFPA), proposing a project integrating land and river electric mobility powered by photovoltaic energy [9]. To substitute fossil fuel consumption in boats, energy produced by photovoltaic systems is regarded as the most appropriate renewable energy source. [10].

Currently, solar boats are defined as vessels equipped with an electric motor powered by electricity sourced from both the grid and an energy storage system, as well as from solar energy converted through photovoltaic modules. This design positions them as an effective alternative for cleaner and more sustainable water transport, significantly reducing greenhouse gas emissions. [11].

The use of photovoltaic systems in boats is a way to generate electricity without constantly relying on fossil fuels. Photovoltaic modules have several advantages as they convert energy silently and, unlike wind turbines, do not have rotating components that could affect the boat's stability [10]. Another way to categorize boats is based on their hull design, which can be monohulls, catamarans, or trimarans [12]. Research indicates that catamaran-structured boats are the most effective for utilizing solar photovoltaic energy. Their flat roofs and optimized space for photovoltaic module installation enable maximum exposure to solar radiation from the beginning of the day. This design minimizes any obstructions to solar rays caused by the boat's structure itself [10].

In this context, the electric boat Poraquê, developed by UFPA, stands out as an innovative example. It uses an electric propulsion system powered by an energy storage system and photovoltaic modules for charging these batteries. Additionally, part of the energy consumed by the boat can be supplied by onshore photovoltaic systems and storage systems, which are part of the DERs. This project demonstrates the feasibility of using distributed energy resources (DERs) in transportation applications in the Amazon. Furthermore, the implementation of a digital twin in the project allows for the optimization of the boat's performance. It also allows for accurate projections of the system's energy consumption, demonstrating how digitalization can complement DERs and enhance energy management efficiency.

This case study highlights the importance of integrating DERs with the electricity grid in the Amazon and underscores the benefits of digitalization for sustainability and operational efficiency, offering valuable insights into the opportunities and challenges in implementing advanced technologies in remote and ecologically sensitive regions.

2. Literature Review

The purpose of this literature review is to conceptually demonstrate the use of digital-twin technology through studies that focus on its application in various scenarios, contexts, and purposes. Digital twins can be classified into different types, such as part twins, unit twins, and process twins, and are applied in various fields including aerospace, automotive, and smart cities [12,13].

Research has demonstrated the expansion of digital-twin usage beyond flow analysis and optimizations, showing applications in planning and managing structures, such as in smart cities [14]. This study illustrates the potential for using digital twins to determine the operation of autonomous vehicles in urban centers, conducting traffic studies and optimizing routes for electric and autonomous vehicles with a focus on energy efficiency and consumption minimization.

Concepts of the lifecycle of systems are presented, covering everything from the theoretical design phase of a project to the end of its stipulated useful life [15]. The lifecycle of a system is seen as a performance indicator for analyzing the wear and tear of electrical components, such as battery health, influenced by various economic or technical aspects, directly impacting production costs. This study demonstrates that the digital twin allows for the implementation of new technologies based on a defined model, enabling the comparison of techniques and system management methods to achieve excellence.

Various challenges regarding electric mobility for autonomous vehicles are presented, highlighting that the dynamism of highways can cause delays in simulations and complicate the understanding of regional dynamics [16]. This study highlights the significance of accurately mirroring real vehicles to effectively represent automated models and optimize load flow for electric chargers. It also discusses the development of a charging station for electric boats in Malaysia, comparing conventional fuel use with electric energy. The focus is on the economic benefits and the reduction of greenhouse gas emissions, particularly when the energy is sourced from renewable resources.

Another important study examines electric mobility in air traffic, specifically focusing on taxis and ambulances operating at low altitudes in urban environments [17]. The application of digital twins facilitates the prediction of potential challenges related to traffic, routing, and weather conditions, thereby enhancing the likelihood of successful implementations. Furthermore, the use of digital twins allows for the complete study of the operation of an electrical mode, with virtual and physical models that communicate, thus obtaining optimal results, as demonstrated by [18]. This study complements the study by [13], which presents the efficiency of vehicle traffic routes.

In addition to digital and technological issues, the energy transition is crucial for reducing climate change, especially in urban centers, which are the major contributors to these problems [19]. In the Amazonian context, the low number of electric vehicles and the implementation of electric mobility projects, such as the SIMA by UFPA, which integrates electric land and water modes with hybrid photovoltaic systems, are essential to address the lack of sustainable modes [20].

Complementary aspects of electric mobility within the European context emphasize that electric vehicles are crucial for lowering greenhouse gas emissions [21–23]. The first and secound paper emphasizes the social, economic, and environmental impacts of incorporating electric modes, as well as the challenges related to the scarcity of raw materials and the generation of energy required for these vehicles. The last paper focuses on the energy transition in Europe, which, although not following the expected projections, shows an increase in electric vehicle sales. It is crucial to ensure the energy transition and the decarbonization of vehicles, promoting the development of renewable energy matrices to combat GHG emissions, with Brazil being a world reference with approximately 88% of its renewable energy matrix [4].

Research has also demonstrated that internal combustion systems are detrimental both environmentally and economically, due to rising fuel tariffs [24]. This study presents a zero-emission conceptual model, simulated via MATLAB/Simulink, using photovoltaic modules and an electrical energy storage system. Challenges such as the seasonality of energy generation curves and the low efficiency of photovoltaic systems are addressed, highlighting that the application of monocrystalline/polycrystalline silicon modules in the Amazonian context is advantageous due to high solar radiation indices and constant temperature, as well as their greater efficiency and positive impact on the stability of vessels [25].

Some experiments have demonstrated the effectiveness of converting conventional boats, which used combustion engines, into electric boats equipped with electric motors combined with energy storage systems, as exemplified in [26], which demonstrates that the electric energy storage system is effective in managing the boat's loads. Other studies present the operation of a solar-electric boat in sunny areas, aiming at the sizing of energy storage systems or the modules for energy generation to charge the batteries, as is the case of [27,28], which use different methods for sizing parameters but present interesting results regarding the final operation of the solar-electric boat. These studies showcase distinct optimization approaches for different operating conditions. The development of all projects involving an energy storage system must be mindful of the battery bank's depth of discharge, as poor optimization can lead to future problems and high costs for the large-scale implementation of boats with this integrated storage system. According to [29], the improper management of battery depth of discharge can significantly reduce the lifespan of the battery and increase operational costs due to more frequent replacements and reduced efficiency.

This brief state-of-the-art study was conducted with the aid of artificial intelligence (AI) for the recommendation of selected works, using a tool named Research Rabbit. Figure 1 presents the main keywords of relevant articles in the research areas used, with the fields of electrical engineering and computer engineering being the most utilized, represented by keywords such as renewable sources and digital twin, respectively. Furthermore, it is possible to analyze the publication years of these academic works, as shown in Figure 2, which indicates that the database is recent, with articles from 2020 onwards. It is important to note that the normalization of these results refers to the most frequent keywords in the database, meaning there may be articles prior to 2020 that do not contain the most relevant keywords for the analyses. The database utilized includes 42 articles from the most renowned bibliographic sources in scientific content for engineering, such as MDPI, IEEE Xplore, and Elsevier.

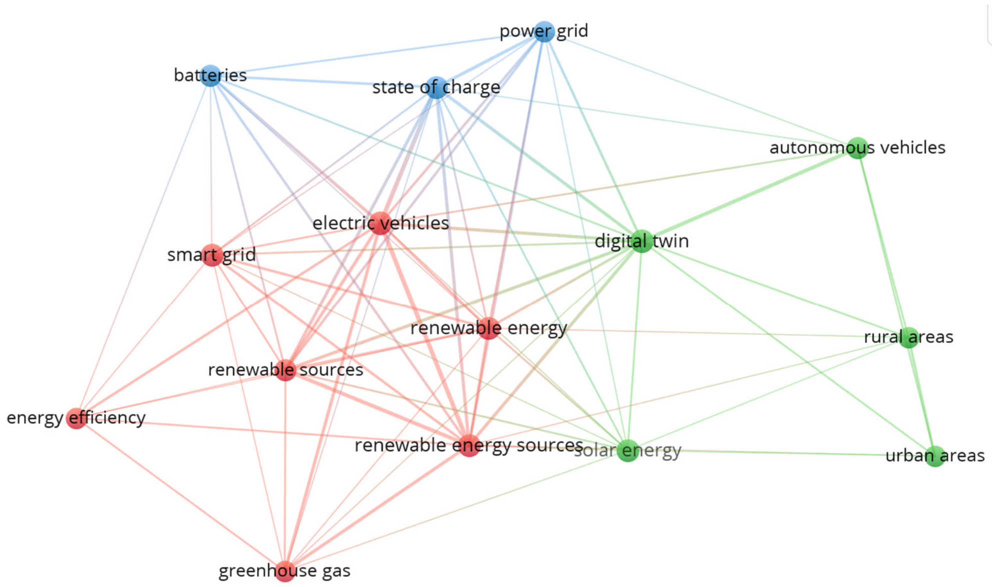

Figure 1. Keyword correlation tree of articles.

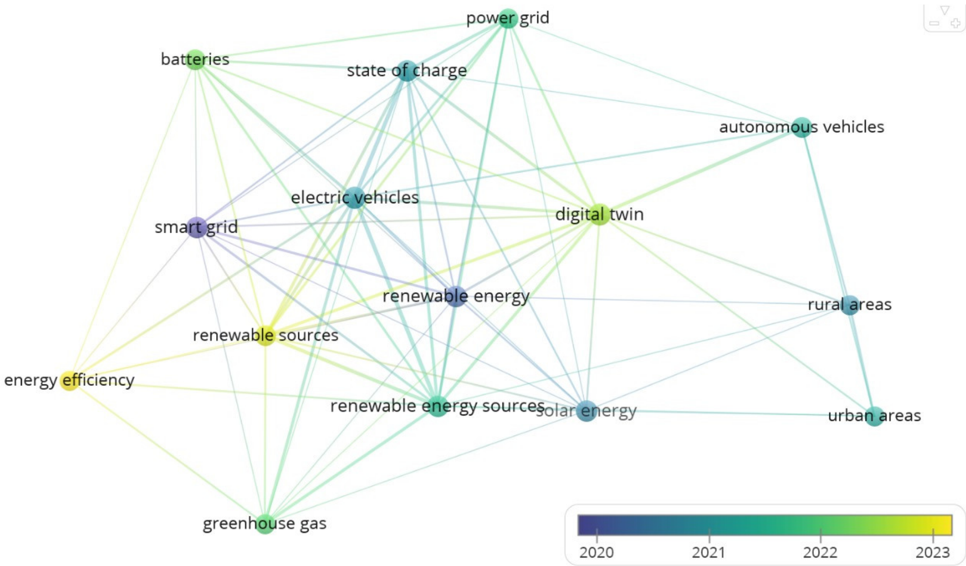

Figure 2. Keyword correlation tree, annual classification.

Therefore, the frequency of recent articles is essential for maintaining the relevance of academic work, making updated publications crucial considering scientific advancements in recent years. This ensures that the research and discussions are aligned with the latest trends, fostering innovation and integration with established methodologies, thereby developing more precise analyses, results, and recommendations.

3. Methodology

The methodology of this study focuses on the creation of a digital-twin model of the electric boat within the SIMA project. This involves the use of software tools such as MATLAB (R2023b Update 4) for modeling the electrical and mechanical elements, both internal and external to the boat, and PVsyst 7.2 for assessing photovoltaic energy generation. The primary objective is to simulate the boat's operation under various conditions to evaluate its performance, energy balance, and greenhouse gas emissions. The results from this study will integrate with other systems already in operation within the SIMA project to provide a comprehensive evaluation of energy balance and emission issues.

3.1. Digital-Twin Modeling

The digital-twin model will be developed using MATLAB, a powerful tool for simulating and analyzing complex systems. This involves creating detailed models of the boat's electrical and mechanical components. The electrical model includes the battery storage system, photovoltaic generation system, and propulsion system, while the mechanical model incorporates aspects such as the boat's structure and hydrodynamics.

MATLAB is widely utilized for 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 [30]. It also features numerous tools that facilitate power system simulations, allowing for the modeling and analysis of dynamic systems. One of these tools is Simulink, which offers a graphical interface where users can employ pre-existing blocks from the software's library, as well as custom blocks, simplifying the modeling approach [31]. In Figure 3, an example of a control system for a boat using Simulink is presented. This is an example of a digital twin, where it is possible to perform various operational analyses of the boat under different conditions, considering both electrical and physical equipment included in the object under study. Various variables can be obtained, such as movement speed, fuel usage, and even the energy used to keep the internal lights on.

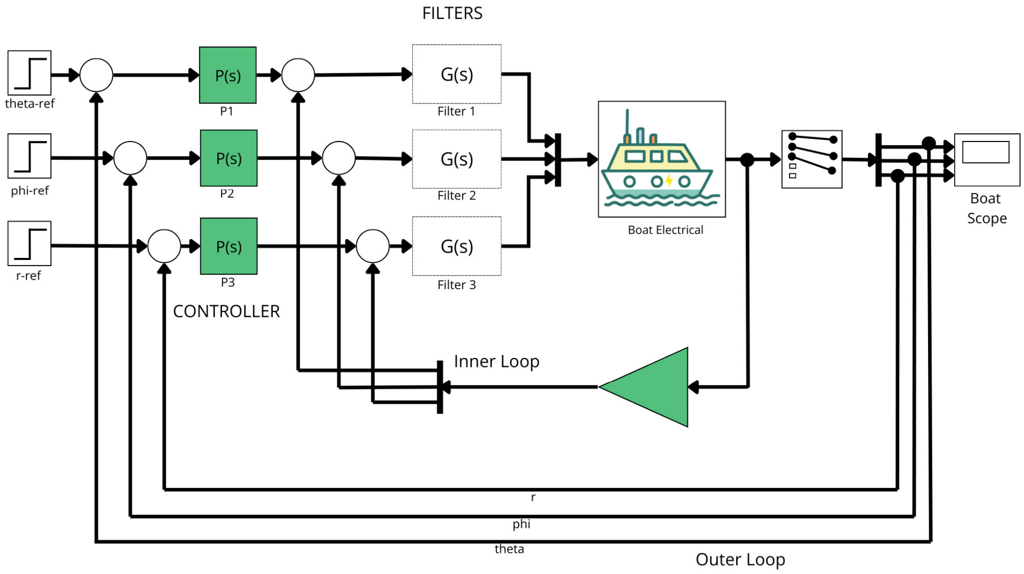

Figure 3. Example of an electric boat control system.

Additionally, there are specific libraries such as Simscape, which is used for various power electronics applications. These specialized libraries aim to simplify the simulation of specific applications, like photovoltaic modules, which are elements of electrical power systems. Thus, it is possible to use basic and specific elements to build a complete physical system [32].

MATLAB also supports the creation of digital twins, which represent a way to evaluate, simulate, and improve real products. By virtually replicating a real physical system, the digital model can provide valuable data on the stability and utilization of the product, such as the product's lifecycle [32].

3.2. Photovoltaic System Simulation

The photovoltaic system simulation is conducted using PVsyst to provide foundational support for the MATLAB simulation of the boat's photovoltaic system. PVsyst analyzes the performance of the photovoltaic modules under the unique meteorological conditions of the Amazon region, including solar irradiance and temperature variations.

The photovoltaic system is configured in PVsyst by specifying the type and number of photovoltaic modules, their arrangement, and their connection to the boat's electrical system. Key parameters such as module orientation, tilt angle, and shading effects are input to ensure accurate modeling. Environmental data specific to the Amazon, such as solar irradiance and temperature, are integrated into PVsyst to accurately predict the photovoltaic system's performance [33].

The simulations account for various impactful variables such as climate, solar irradiance, and precipitation, considering the system's location. Location differences are observed through parameters like latitude, longitude, and altitude [34], which directly affect the climatic conditions in a region. These factors influence the amount of solar irradiance reaching the system due to the region's cloud cover.

PVsyst simulates the energy output of the photovoltaic system over various periods, providing detailed reports on expected energy production. These results are used to inform the MATLAB simulation, ensuring realistic energy input data, as energy generation fluctuates throughout the year due to daily variations in the sun's position. The integration of the photovoltaic system with the boat's electrical system is evaluated to ensure compatibility with the battery storage and propulsion systems. PVsyst also helps identify optimization strategies to enhance the system's efficiency and reliability.

By utilizing PVsyst for initial simulations, accurate input data for MATLAB are provided, enabling a comprehensive evaluation of the photovoltaic system's performance and supporting the SIMA project's goal of sustainable mobility in the Amazon region.

3.3. Financial and Ecological Comparison

Using the data from the digital-twin model and photovoltaic system simulation, this study assesses the greenhouse gas emissions of the electric boat. The goal is to identify scenarios where the boat operates most efficiently, minimizing emissions and maximizing energy use.

To perform the financial and ecological analysis, comparisons were made between the operating costs of this electric boat and an equivalent internal combustion engine boat. An estimation of the total energy consumption of the solar boat on a typical sunny day was developed. Using the installed peak power values (Pp), the average PVOUT is obtained, based on the specific production calculated by PVsyst of 4.21 kWh/kWp/day (annual average value).

The comparison between the systems considers the available generated energy—total energy (Etotal), obtained through simulation—and the theoretical total consumption (Ctotal). The three possible scenarios are shown in Table 1.

Table 1. Performance scenarios based on the relationship between energy generation and consumption.

Scenario	Description	Performance Evaluation
Etotal > Ctotal	The generated energy exceeds consumption	The system operates with an energy surplus, ensuring reliable performance and stability.
Etotal = Ctotal	The generated energy matches consumption	The system requires optimal operational efficiency to maintain a balanced state.
Etotal < Ctotal	The generated energy is insufficient to meet consumption	The system will fail to operate efficiently within the defined period due to energy deficit.

The total available energy in a service day is calculated as shown in Equation (1), where E_{total} is the sum of the energies from the photovoltaic modules ($E_{modules}$) and the storage system ($E_{batteries}$):

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

Subsequently, the energy consumption in the propulsion system is calculated based on the engine load and its usage percentage to maintain cruising speed, as shown in Equation (2). The Ctotal is the relation between the engine power (Pengine), the number of engines (n), and the engine usage percentage at cruising speed (Pu):

$$\text{Ctotal} = \text{Pengine} \times \text{A} \times \text{n} \times \text{Pu} \quad (2)$$

Based on these results of Ctotal, the daily and monthly cost of electricity consumed from the grid for the catamaran can be calculated considering different tariff types, such as single-rate tariffs and time-of-use tariffs (peak and off-peak), as shown in Table 2, obtained from the local energy concessionaire in 2022. The exchange rate considered was 5.66 BRL/USD, and the values were converted accordingly.

Table 2. Daily cost of boat electricity.

Fare Type	Price (BRL/kWh)	Price (USD/kWh)	Grid Energy (kWh)
Single Rate	BRL 0.88	USD 0.16	45.15
Peak	BRL 3.59	USD 0.63	45.15
Off-Peak	BRL 0.33	USD 0.06	45.15

For a catamaran with a cruising speed of 8 knots (approximately 7.3 knots for a solar boat), the estimated consumption is 20 L per hour of operation. Thus, the consumption for the same autonomy of 3 h and 5 min and the cost of fuel were calculated, considering the average price of nautical diesel for 2022, as shown in Equation (3):

$$C_{Dtotal} = (C_{D/h} \times A) \tag{3}$$

where C_{Dtotal} is the total diesel consumption in liters, and $C_{D/h}$ is the hourly diesel consumption. Based on Equation (3), the total consumption is 61.6 L.

Diesel-powered vehicles emit more CO_2 per unit volume or weight of fuel compared to other motorized modes. In this study, an average emission factor of 2.6 kg of CO_2 per liter of diesel burned was used, plus an average of 0.5 kg of CO_2 emitted to produce and distribute the fuel, resulting in a total emission rate of approximately 3.2 kg of CO_2 per liter of diesel. The total daily CO_2 emission is calculated using Equation (4):

$$E_{tCO_2} = (E_{pCO_2} + E_{qCO_2}) * Vd \tag{4}$$

where E_{tCO_2} is the total CO_2 emission, E_{pCO_2} is the CO_2 emission from producing 1 L of diesel, E_{qCO_2} is the CO_2 emission from burning 1 L of diesel, and Vd is the daily volume of diesel, totaling 197.12 kg/day.

By incorporating these methodologies, this study aims to provide a comprehensive evaluation of the electric boat's environmental impact and its potential for reducing greenhouse gas emissions, thereby supporting the broader objectives of the SIMA project in promoting sustainable mobility in the Amazon region.

4. Subject of Study: SIMA PROJECT

The Intelligent Multimodal System of the Amazon (SIMA) project is an initiative of the UFPA in partnership with Norte Energia and the Center for Research and Development in Telecommunications (CPqD). Its objective is to promote sustainable mobility in the Amazon region based on the pilot project installed at the Guamá campus of UFPA through electric modes, including electric buses and boats, supported by photovoltaic generation and energy storage systems [20,35,36]. The topology is presented in Figure 4.

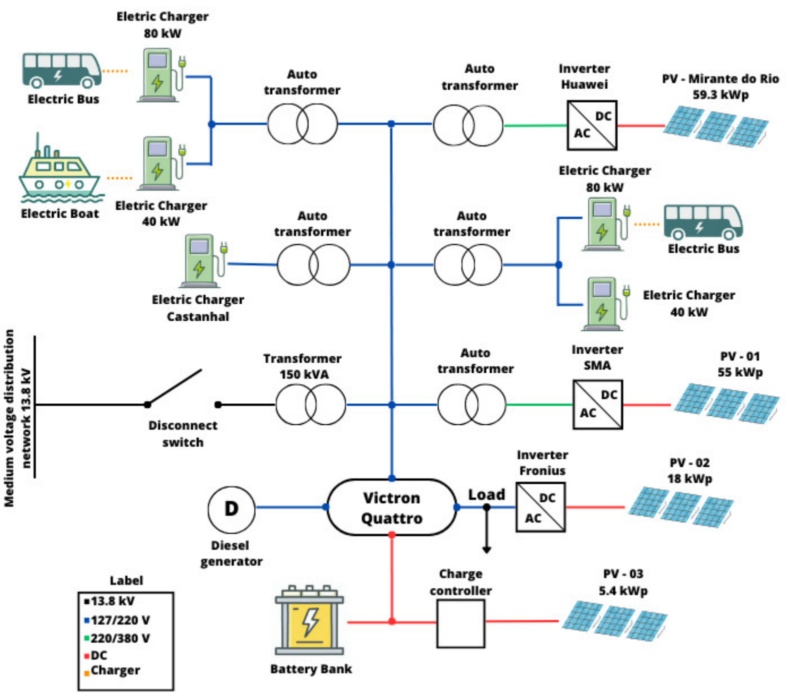

Figure 4. Topology of the SIMA project.

4.1. Supporting Energy Infrastructure and Electric Mobility

The supporting energy infrastructure of the SIMA project consists of photovoltaic generation systems, energy storage, and charging stations for electric vehicles. These systems are integrated to create distributed energy resources (DERs), characterized by decentralized energy generation and the intelligent management of energy flows.

4.1.1. Photovoltaic Generation Systems

Two main photovoltaic generation systems are in operation on the Guamá campus:

- **The Mirante do Rio Photovoltaic System, Belém-Pa, Brazil.**

  Power: 59.29 kWp.
  Modules: 177 photovoltaic modules of 335 Wp (BYD).
  Inverter: 60 kW
  Connection: On-grid.

- **The Ceamazon Hybrid Mini-grid, Belém-Pa, Brazil.**

  Power: 78.39 kWp.

Components: SMA system: 54.94 kWp (on-grid/hybrid), Fronius system: 18.09 kWp (on-grid/hybrid), Victron system: 5.36 kWp (off-grid/hybrid).

Biodiesel Generator: Backup for extreme cases.

Connection: Part of the system is connected to the internal mini-grid, while another part is connected to the UFPA grid.

4.1.2. Energy Storage System

The energy storage system uses lithium-ion batteries to ensure the continuous operation of electric modes. Specifications:

Total Capacity: 110.4 kWh.

Technology: BYD batteries, with 80% depth of discharge.

Management: Interconnected controllers manage battery charge and discharge, maintaining system efficiency and safety.

4.1.3. Charging Stations

The Guamá campus has four charging stations for electric vehicles, strategically located next to the sports hall and CEAMAZON. Specifications of the main models:

- **The BYD EVA080KI/01 Charging Station, Belém-Pa, Brazil.**

  Output Power: 80 kVA.
  Input Voltage: 380–480 V AC.
  Output Current: ≤126 A AC.

- **The ABB TERRA 54HV Charging Station, Belém-Pa, Brazil.**

  Output Power: 50 kW.
  Maximum Output Current: 125 A DC.
  DC Output Range: 200–950 V DC.

4.1.4. Real-Time Monitoring

A real-time monitoring system has been developed to collect and analyze data from electric modes. Variables such as current, voltage, and power are continuously monitored, facilitating the efficient management and preventive maintenance of the systems. This system uses sensor technology and cloud data transmission, providing managers with accurate and up-to-date information.

4.2. Electric Mobility Modes

SIMA introduced three electric mobility modes on campus: two electric buses and a solar-electric boat.

4.2.1. Electric Buses

The buses, both intercity and urban models, have permanent magnet synchronous motors with a nominal power of 110 kW each and BYD LiFePO4 batteries with a capacity of 324 kWh, offering a range of up to 250 km.

- **Intercity Bus, Belém-Pa, Brazil.**

  Motor: Two permanent magnet synchronous motors, 110 kW each.
  Battery: BYD LiFePO4, 324 kWh.
  Range: 250 km.
  Charging: 4–5 h, power 2× 40 kW AC.
  Operation: Daily trip UFPA Belém campus—Castanhal.

- **Urban Bus, Belém-Pa, Brazil.**

  Motor: Two synchronous motors, 110 kW each.
  Battery: BYD LiFePO4, 324 kWh.
  Range: 250 km.
  Charging: 4–5 h, power 2× 40 kW AC.
  Operation: Internal transport on the Guamá campus.

4.2.2. Solar-Electric Boat

The project includes a solar-electric boat in the final stages of implementation, which is the main study object of this work. The SIMA project's solar-electric boat is a catamaran equipped with an integrated photovoltaic system and energy storage system. The topology is presented in Figure 5, and it is designed to operate efficiently and sustainably in the Amazon rivers. Table 3 presents the physical specifications of the electric boat, including length, width, and structure weight.

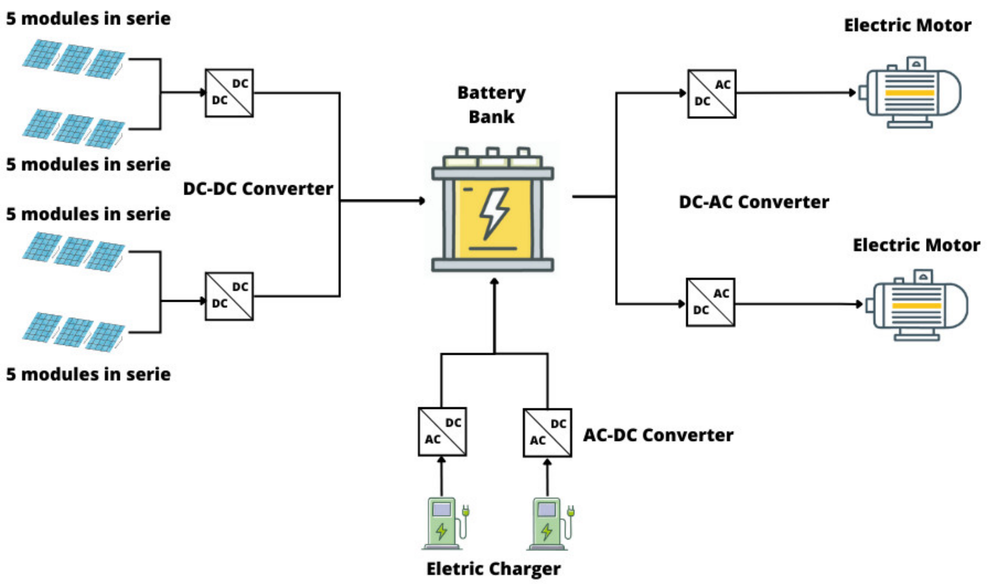

Figure 5. Topology of the solar-electric boat.

Table 3. Physical specifications.

Specifications	Value
Length	12.3 m
Width	6 m
Weight of the structure	1386 kg

Meanwhile, Table 4 presents various characteristics of the electric boat's propulsion system, such as motor information, power, and technical details. These specifications are essential to understand the performance capacity and efficiency of the boat in daily operations.

Table 4. Propulsion system specifications.

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

Furthermore, Table 5 presents the parameters of the photovoltaic system and storage system, such as power, quantity, and weight, among other parameters. These details are crucial to evaluate the feasibility of using photovoltaic energy on the boat and ensure it can operate efficiently and sustainably during its trips.

Table 5. Photovoltaic nad storage system specifications.

Parameters	Value
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	14,760 Ah
Quantity of batteries	72

5. Results

The digital-twin model of the electric boat accurately simulates the boat's electrical and mechanical components under various operational scenarios. The model provides detailed insights into the boat's energy consumption, propulsion system performance, and overall efficiency.

5.1. Photovoltaic Modules

The photovoltaic system simulation utilized the PVarray block from the Simscape library to model the arrangement of photovoltaic modules. This block requires two key parameter inputs: irradiation and temperature. In addition to these inputs, the block has three outputs: a negative pole, a positive pole for voltage measurements, and an output labeled "m" for displaying measured parameters. Figure 6 illustrates the block representing the photovoltaic generation system.

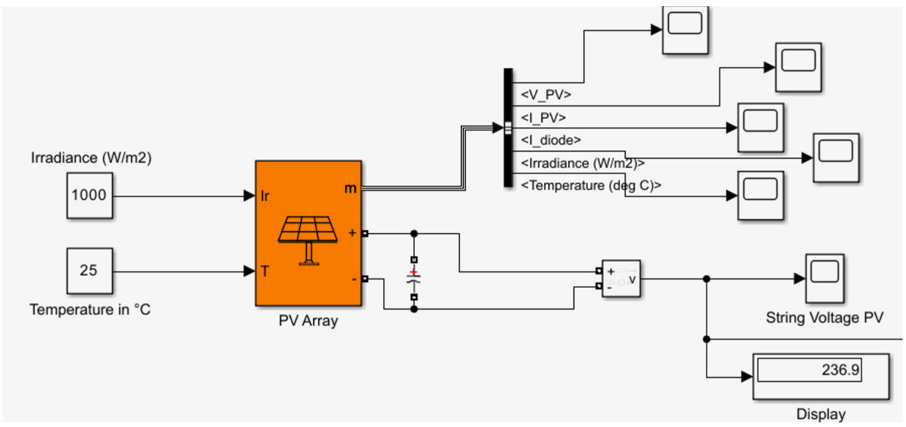

Figure 6. Photovoltaic system of the electric boat highlighting the PVarray block in orange.

To assess the performance under different environmental conditions, simulations were conducted with varying ambient temperatures. Figure 7 presents the current and power curves as functions of voltage for scenarios with ambient temperatures of 25 °C and 45 °C.

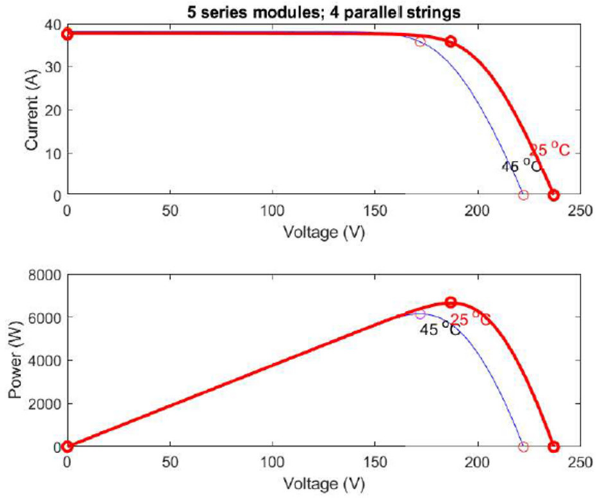

Figure 7. Current and power curves as a function of voltage for temperatures of 25 °C and 45 °C.

For the specific case defined in the schematic input, with an irradiance of 1000 W/m^2 and a temperature of 30 °C, the simulation indicates a voltage output of 233.2 V, as shown in Figure 8.

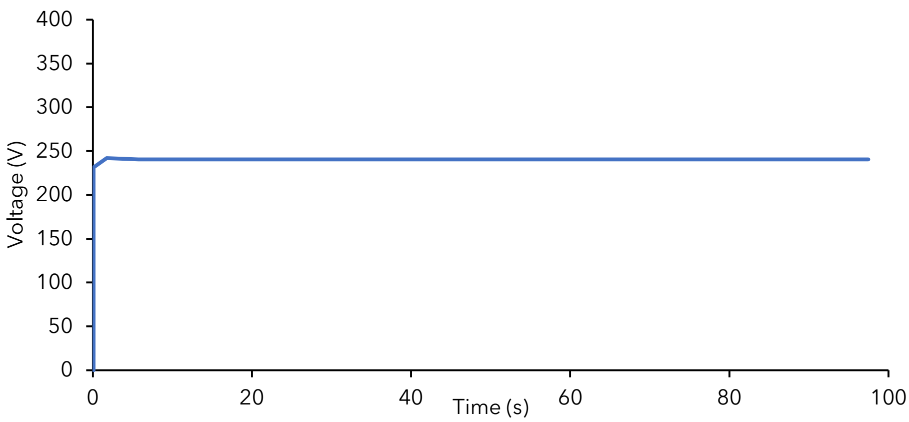

Figure 8. Output voltage of the photovoltaic system.

Given that the battery bank charging voltage is 72 V, which is lower than the PV array output voltage, a DC-DC converter is essential to adjust the voltage output to match the input voltage of the battery bank. This step ensures efficient charging and energy transfer between the photovoltaic system and the battery storage.

Optimizing the photovoltaic system involves ensuring the proper alignment of the modules to maximize solar exposure and implementing a monitoring system to track performance metrics. These data help maintain efficiency and inform potential adjustments or upgrades. Additionally, integrating the photovoltaic system with the boat's overall energy management system allows for real-time adjustments based on energy demand and storage capacity. This integration enhances operational efficiency and supports the SIMA project's sustainability goals by maximizing renewable energy use and minimizing dependency on external sources.

The simulation results highlight the importance of considering environmental factors such as temperature and irradiation when designing photovoltaic systems. By accounting for these variables, the system can be optimized for the specific meteorological conditions of the Amazon region, supporting the project's objectives of promoting clean and sustainable energy solutions.

5.2. DC-DC Converter

The DC-DC converter is crucial in photovoltaic systems, performing tasks like optimizing power generation through maximum power point tracking (MPPT) and aligning voltage for battery charging. In this project, the converter regulates the voltage to 72 V, ensuring compatibility with the storage system. Figure 9 displays the converter model in Simulink, and Figure 10 shows the photovoltaic system's output voltage after conversion.

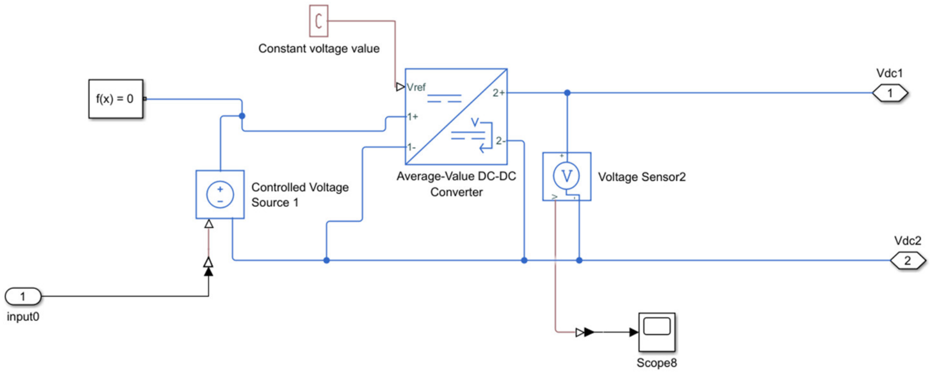

Figure 9. DC-DC converter in Simulink.

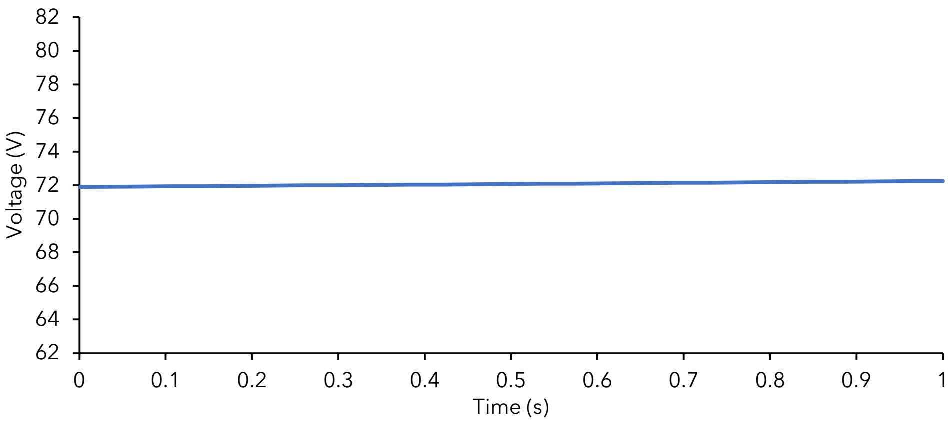

Figure 10. DC-DC converter output voltage.

Beyond simple voltage regulation, the converter dynamically adjusts to maintain system efficiency, compensating for variations in irradiation and temperature. This ensures the optimal operation of the photovoltaic modules, maximizing energy capture and conversion. Using MPPT algorithms within the converter enhances the system's adaptability to changing environmental conditions, improving overall performance and reliability.

Integrating the DC-DC converter into the photovoltaic system enhances compatibility with the storage system and contributes to the energy management setup's longevity and stability. By maintaining consistent voltage levels, the converter prevents the overcharging or undercharging of the batteries, thereby extending their lifespan and efficiency. This integration is essential for the electric boat's operation within the SIMA project, ensuring the effective and sustainable use of renewable energy.

5.3. Battery Bank

The Simscape battery block was used to represent the storage system, as shown in Figure 11. Three battery blocks are connected in parallel, with the main parameters being a nominal voltage of 76.8 V and a capacity of 205 Ah per block (Figure 12). This configuration results in a total storage capacity of 615 Ah.

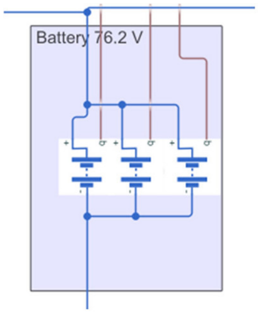

Figure 11. Battery bank represented in Simulink.

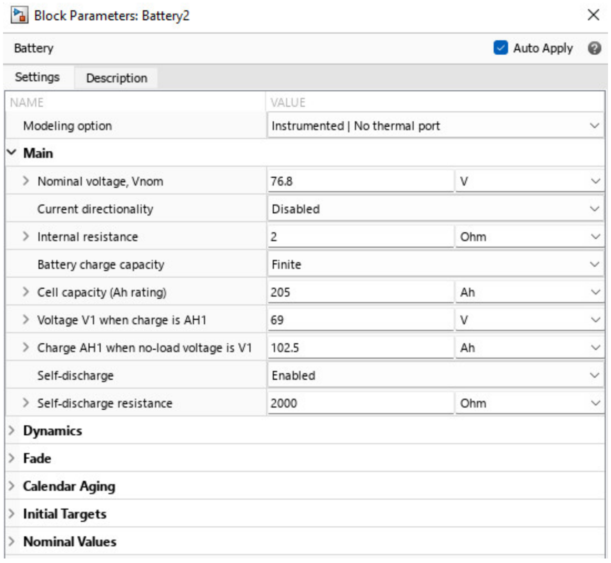

Figure 12. Storage system parameters.

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 Figure 13.

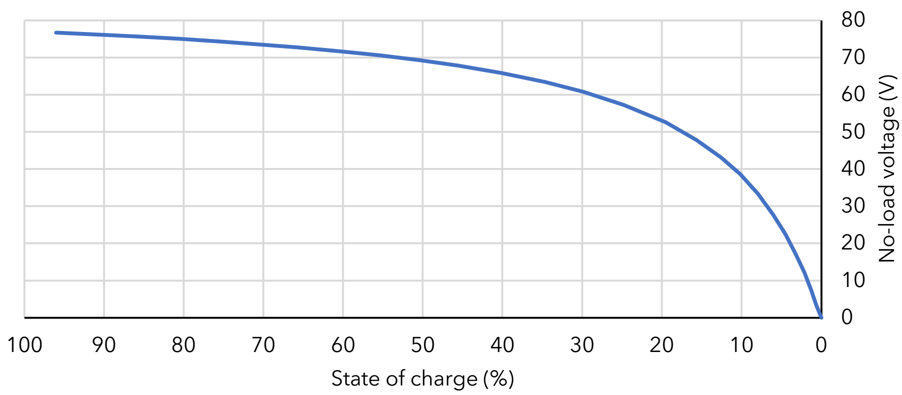

Figure 13. Storage system discharge curve.

Integrating this battery bank with the photovoltaic system and the DC-DC converter ensures efficient energy storage and management. The system can store sufficient energy to meet the boat's daily operational needs, supporting its sustainable and independent operation. This integration is key to achieving the SIMA project's goals of promoting clean and renewable energy in the Amazon region.

5.4. DC-AC Converter

The DC-AC inverter is a crucial component of the system, converting the DC voltage from the bus—where the photovoltaic generator and storage system are connected—into AC voltage at the specifications required by the electric motors. In the original design, two inverters divide the power, but in the simulation, a single average-value inverter (three phases) block is used to perform the entire conversion process. Figure 14 shows the block with positive and negative DC inputs and the three-phase AC output on phases ABC.

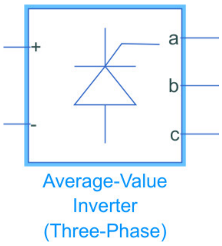

Figure 14. Electric inverter block.

The parameter configurations for the inverter block were selected based on the motor specifications: three phases at 60 Hz, a 120° phase shift, and an output voltage of 51 V, as shown in Figure 15.

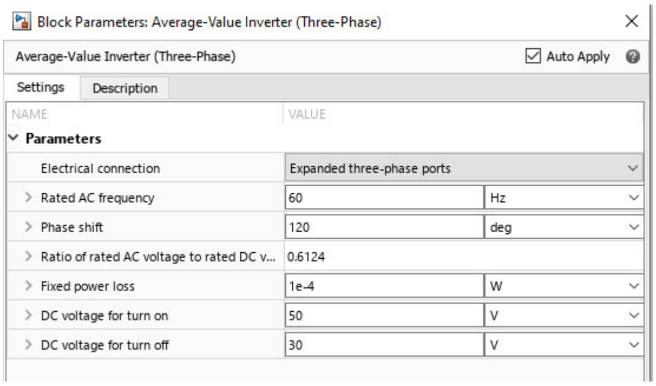

Figure 15. Inverter block parameters.

Thus, the energy signal at the inverter output, with maximum voltage values of 53 V and a frequency of 60 Hz, is depicted in Figure 16.

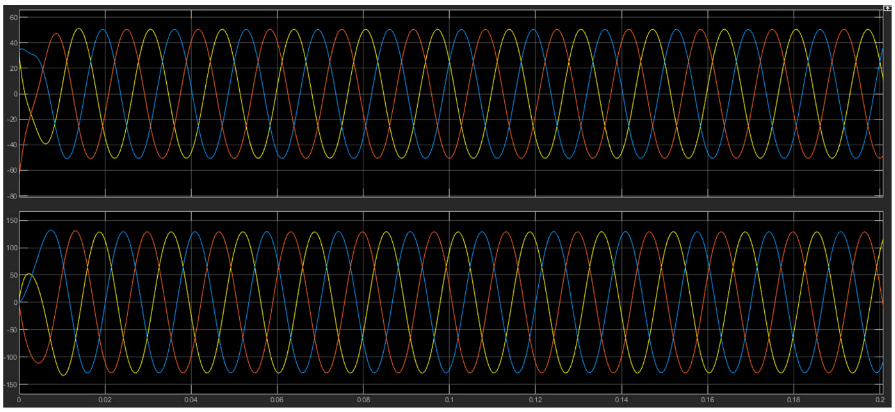

Figure 16. Graph of voltage and current at the inverter output.

This conversion process is vital for ensuring that the energy generated and stored by the photovoltaic and battery systems is effectively utilized by the boat's electric motors, contributing to the overall efficiency and sustainability of the system.

5.5. Motors

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 shown in Figure 17, two motors connected in delta configuration were placed just after the frequency inverter. This block has two outputs: R, the mechanical rotational port associated with the machine rotor, which transmits the values of angular speed, and the output torque of the motor.

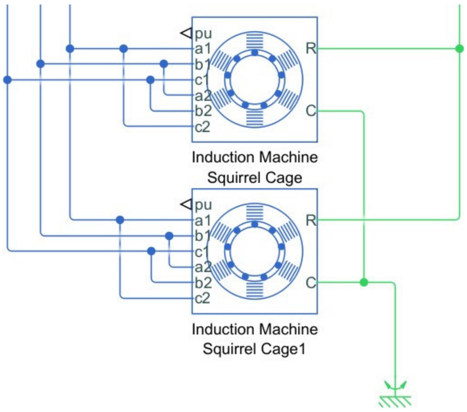

Figure 17. Block of three-phase motors for boat propulsion.

The design parameters were added to the simulation for each motor with 13 kW of power and a nominal voltage of 51 V in a three-phase alternating current at a frequency of 60 Hz, as depicted in Figure 18.

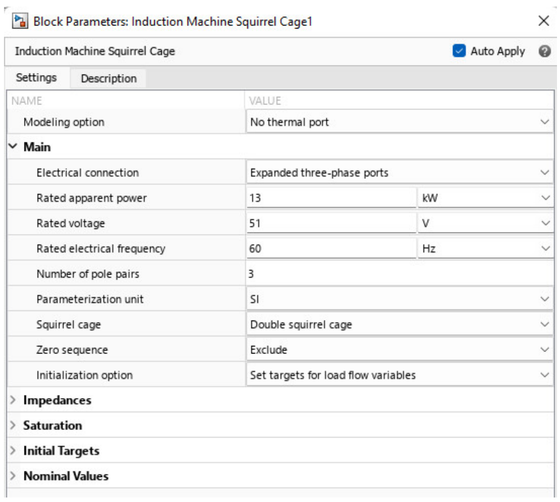

Figure 18. Parameters of the induction-machine block.

These parameters ensure that the motors are accurately represented in the simulation, reflecting the real-world operational characteristics necessary for efficient boat propulsion.

5.6. AC-DC Converter

Since the photovoltaic generation system does not supply all the energy needed for the boat's daily autonomy, a power supply for recharging at land-based charging stations is necessary. Therefore, an AC-DC converter was developed to transform the 127 V AC from the UFPA power grid into the continuous 72 V DC required for the battery bank. A subsystem was created in Simulink, featuring an alternative voltage source to represent the energy input, a switching mechanism controlled by a step block to indicate when it is on or off, and the AC-DC converter power source subsystem, as shown in Figure 19.

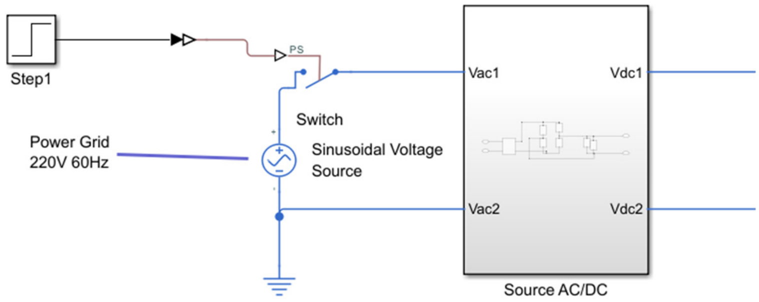

Figure 19. AC-DC converter subsystem.

The converter source diagram was built based on a simple analog electronics circuit, which includes a voltage transformer, a rectifying bridge with diodes, and a capacitor. This circuit allows for the unilateral conversion of the alternating current from the university grid into direct current for battery charging. The source circuit is depicted in Figure 20.

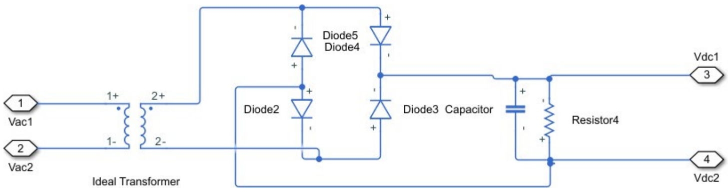

Figure 20. AC-DC converter source.

5.7. Physical Representation of the Boat

The physical representation of the boat follows the motors and includes three measurement blocks and four system representation blocks. The measurement blocks are as follows: an angular velocity meter at the motor output (measuring in rad/s, converted to rpm), a force meter showing the projected force on the boat (in Newtons), and a linear velocity meter showing the boat's cruise speed (initially in m/s, converted to knots).

The system representation blocks consist of a gearbox to increase torque and propulsion, a wheel-and-axle block that converts wheel and axle size, and angular rotation speed and torque data to produce a propulsion output force. Additionally, there are blocks representing the boat's inertia, considering a mass of 1389 kg plus 20 passengers averaging 70 kg each, totaling 2789 kg. Finally, a block simulates the friction force between the boat and the water, set at 150 N/(m/s). The complete system is shown in Figure 21.

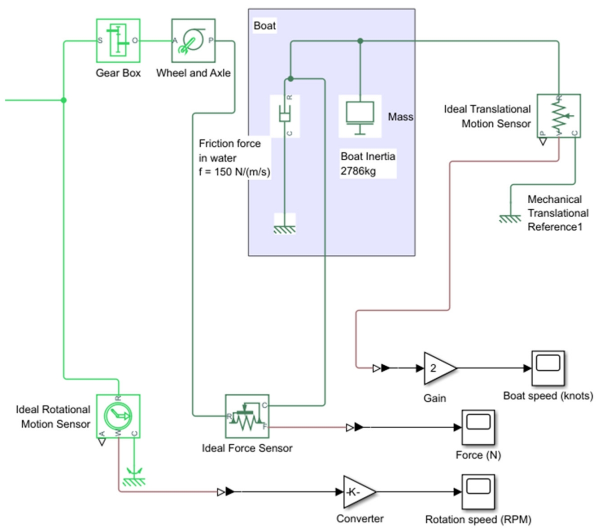

Figure 21. System for representing the physical parameters of the boat.

Using these sensors, various scenarios were simulated to evaluate the boat's operation. Figure 22 shows the result of a 100 s full power simulation, where the boat reached its maximum design speed of 10 knots in 40 s. Another simulation, using the total autonomy time of 3 h and 5 min (11,100 s) at cruising speed, achieved the expected result, maintaining speed throughout the period with constant irradiation at 1000 W/m^2, as shown in Figure 23.

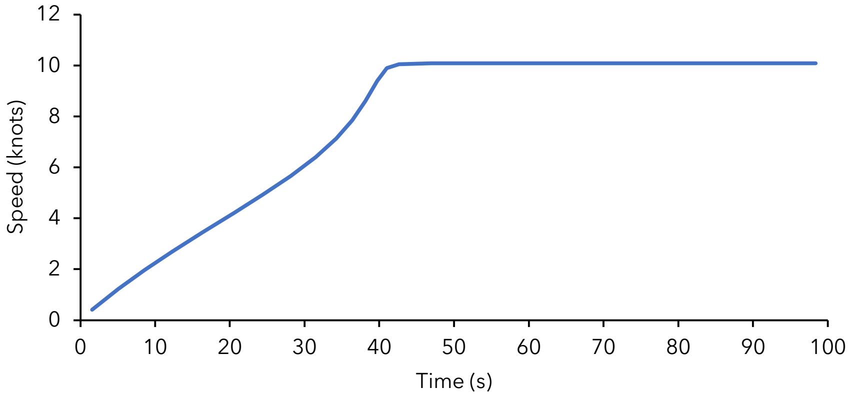

Figure 22. Graph of boat speed in knots.

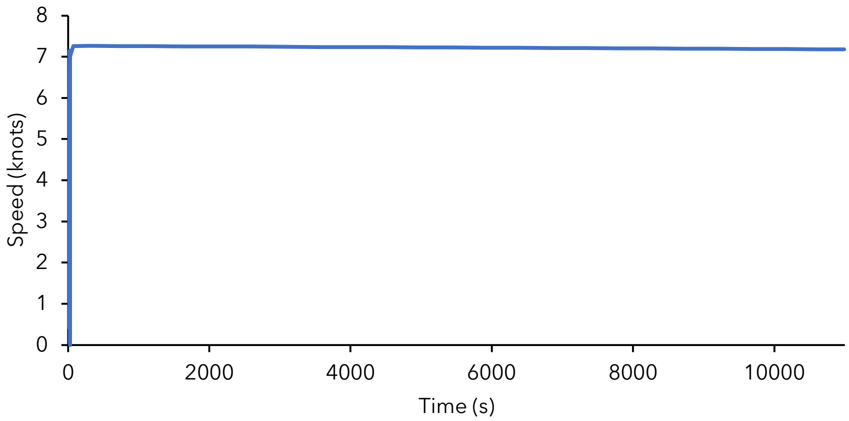

Figure 23. Graph of boat speed in knots for full range.

5.8. Financial and Ecological Comparison

To evaluate the economic and environmental impact of the electric boat, a comprehensive comparison was made between its operational costs and emissions and those of a conventional internal combustion engine boat. Table 6 shows the energy parameters obtained through simulation, including values for PVOut, Ebatteries, and Emodules.

Table 6. Metrics obtained in simulation for electrical energy generation and battery discharge.

PVOut (kWh/kWp/Day)	Ebatteries (kWh)	Emodules (kWh)
4.21	47.23	28.20

The energy generated by the modules is 28.20 kWh, and the energy available in the storage system is 47.23 kWh, resulting in a total energy of 75.43 kWh for the operation of the electric boat. Upon calculation, 73.35 kWh is needed for the boat's operation, as shown in Equations (2) and (3). Therefore, the specified storage and generation values are sufficient for the proposed autonomy, as Etotal is greater than Ctotal, with a daily consumption coverage rate of 38% of the photovoltaic generation system, while the remaining 62% of the battery charge will be recharged at the university's charging stations.

The daily fuel cost was calculated using the average diesel price in 2022, as shown in Table 2. It can be observed that the diesel cost is more than 10 times higher than the electricity cost for the solar boat. Table 7 shows the total consumption, diesel price, and daily and monthly costs, with values converted to USD at an exchange rate of 5.66 BRL/USD.

Table 7. Consumption metrics, diesel price, and daily and monthly costs.

Total Daily Consumption (L)	Diesel Price (USD/L)	Diesel Daily Cost (USD)	Diesel Monthly Cost (USD)
61.6	USD 1.20	USD 73.66	USD 2209.80

Considering that the electricity generation source is renewable and non-polluting, it is possible to calculate the number of tons of CO_2 avoided annually. The annual CO_2 emissions amount to 71,948.8 kg/year, or nearly 72 tons of pollutants per year. The contribution of such a modal to the environment is evident, with significantly lower maintenance costs and potentially faster investment returns if off-peak charging strategies are utilized.

5.9. Estimated Energy Balance

Based on the daily energy consumption of the electric boat, an annual consumption of approximately 26.77 kWh was estimated. This estimation allowed us to analyze the impact of adding this load to the SIMA project's overall energy balance.

Considering the distributed energy resources (DERs) outlined in Section 4, the annual photovoltaic generation capacity is around 206 MWh. The operational loads, including electric buses and other systems, consume approximately 169.63 MWh annually. Figure 24 illustrates the energy balance for the SIMA project, including the primary DERs, operational loads, and the projected consumption of the electric boat.

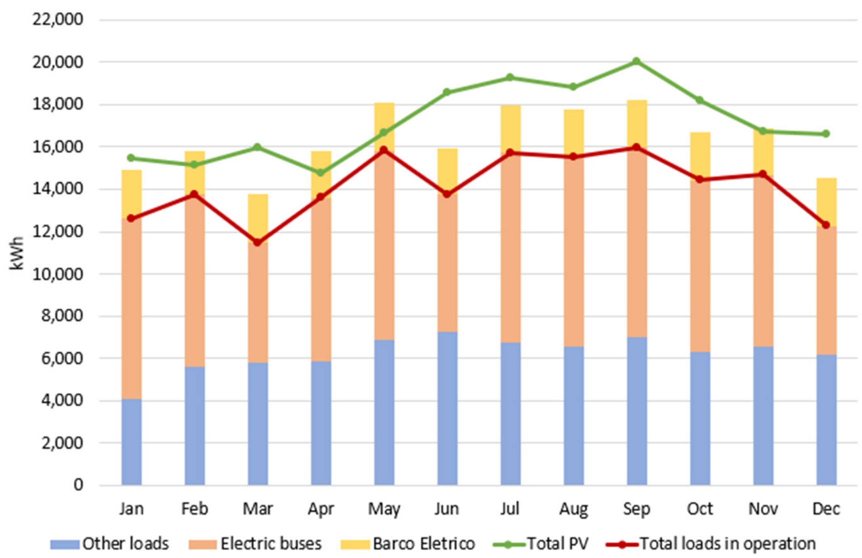

Figure 24. Energy balance of the SIMA project.

In the months of February, April, May, and November, the energy consumption slightly exceeded the energy generated by the photovoltaic systems. However, considering the increased generation during other months, the total load for the SIMA project represents 95% of the total energy generated. As a result, the project is still considered 100% supplied by photovoltaic energy, maintaining its status as a zero-energy and low-carbon project.

6. Conclusions

The implementation of electric mobility through the SIMA project represents a significant step toward sustainable energy use in transportation, especially in the Amazon region, where river-based mobility is essential. By integrating distributed energy resources (DERs) with advanced real-time monitoring and energy management, the project has successfully maintained a balanced energy system. This has enabled the operation of electric buses and boats powered entirely by photovoltaic energy, furthering the region's sustainability goals.

The UFPA electric boat, Poraquê, is a remarkable demonstration of the feasibility of using renewable energy for transportation in remote and ecologically sensitive areas. This boat alone contributes to the annual reduction of approximately 72 tons of CO_2 emissions, showcasing the immense environmental benefits of this project. Moreover, the successful deployment of digital-twin technology has provided a prediction of energy consumption forecasting, which has been crucial in managing energy loads efficiently.

The optimization of the boat's operation is an ongoing process, which will begin in earnest once the boat enters into real-world operation and operational data are collected. The real boat is expected to start operating in the coming months, at which point the final validation of the developed digital-twin model will be possible, allowing for comparisons with the real boat's performance characteristics. Nevertheless, this article has already demonstrated that the model functions within standard conditions. The validation of the digital-twin model in this paper is achieved through the detailed analysis of each component within the boat's powertrain system.

Although the project can face challenges in energy generation during specific months, the overall energy performance of the photovoltaic systems ensured that 100% of the project's energy demands were met through renewable sources. This achievement solidifies the SIMA project as a zero-energy, low-carbon initiative, demonstrating the feasibility of achieving energy self-sufficiency in complex environments.

Looking ahead, expanding the deployment of DERs, optimizing energy storage systems, and further advancing digital-twin technologies will be crucial for scaling these innovations to broader transportation networks. This will further reduce the environmental impact and contribute to the global transition toward clean, renewable energy in transportation. The SIMA project not only sets a strong example of the benefits of integrating renewable energy with mobility solutions but also offers a scalable model for other regions seeking to achieve similar sustainability outcomes.

By embracing such innovative energy solutions, the project serves as a beacon of hope for future transportation systems worldwide, leading the way for the widespread adoption of low-emission, renewable-powered mobility.

Author Contributions: B.S.d.A. and A.L.L.d.N. developed the entire study in addition to conducting data acquisition, modeling and analysis of the results obtained. B.S.d.A. and A.L.L.d.N. wrote the original draft and edited the text, while M.E.d.L.T., U.H.B. and C.C.M.d.M.C. reviewed and supervised the study. All authors discussed the results and conclusions of the manuscript. All authors have read and agreed to the published version of the manuscript.

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References

1. Daulatabad, N.A.; Rajatha, M.; Maheshwari, B.M.; Hemanth, H.A.; Shankar, S. Smart Grid and the Importance of Electric Vehicles. In Proceedings of the IEEE International Conference on Distributed Computing and Electrical Circuits and Electronics (ICDCECE), Ballari, India, 23–24 April 2022. [CrossRef]
2. Ibrahim, M.S.; Dong, W.; Yang, Q. Machine learning driven smart electric power systems: Current trends and new perspectives. *Appl. Energy* **2020**, *272*, 115237. [CrossRef]
3. Eurostats. Available online: https://ec.europa.eu/eurostat/statistics-explained/ (accessed on 24 July 2024).
4. EPE—Empresa de Pesquisa Energética. *Balanço Energético Nacional*; EPE: Brasília, Brazil, 2023.
5. IEPA—Instituto de Pesquisa Econômica Aplicada. *Política Energética no BRICS: Desafios da Transição Energética*; IEPA: Rio de Janeiro, Brazil, 2023.
6. Al-Ismail, F.S.; Alam, M.S.; Shafiullah, M.; Hossain, M.I.; Rahman, S.M. Impacts of Renewable Energy Generation on Greenhouse Gas Emissions in Saudi Arabia: A Comprehensive Review. *Sustainability* **2023**, *15*, 5069. [CrossRef]
7. ICCT—The Internetional Council on Clean Transportation. Available online: https://theicct.org/publication/a-global-comparison-of-the-life-cycle-greenhouse-gas-emissions-of-combustion-engine-and-electric-passenger-cars/ (accessed on 24 July 2024).
8. Francisquini, S. A Infraestrutura para Utilização do Transporte Fluvial no Brasil e a Lei dos Portos. *Rev. Científica Sem. Acadêmica* **2021**.
9. Tostes, M.E.L.; Souza, A.P.F.; Tabora, J.M.; Palheta, M.S.S.; Duarte, A.R.; Soares, T.M.; Nascimento, A. Aplicação dos objetivos do desenvolvimento sustentável na Amazônia: Um estudo de caso na Universidade Federal Do Pará (UFPA). *Peer Rev.* **2023**, *5*, 365–379. [CrossRef]
10. Kurniawa, A. A Review of Solar-Powered Boat Development. *J. Technol. Sci.* **2016**, *27*, 185–192.
11. Minak, G. Solar Energy-Powered Boats: State of the Art and Perspectives. *J. Mar. Sci. Eng.* **2023**, *11*, 1519. [CrossRef]
12. Oliveira, M.; Suemitsu, W. Uma análise do desenvolvimento dos barcos solares. *Conex.—Ciência E Tecnol.* **2017**, *11*, 101–108.
13. Ibrahim, M.; Rassõlkin, A.; Vaimann, T.; Kallaste, A. Overview on Digital Twin for Autonomous Electrical Vehicles Propulsion Drive System. *Sustainability* **2022**, *14*, 601. [CrossRef]
14. Yeon, H.; Eom, T.; Jang, K.; Yeo, J. DTUMOS, digital twin for large-scale urban mobility operating system. *Sci. Rep.* **2023**, *13*, 5154. [CrossRef]
15. Khalyasmaa, A.I.; Stepanova, A.I.; Eroshenko, S.A.; Matrenin, P.V. Review of the Digital Twin Technology Applications for Electrical Equipment Lifecycle Management. *Mathematics* **2023**, *11*, 1315. [CrossRef]
16. Salleh, N.A.S.; Muda, W.M.M.; Umar, R. Optimization and Economic Analysis of Grid-Photovoltaic Electric Boat Charging Station in Kuala Terengganu. *MATEC Web Conf.* **2016**, *74*, 22. [CrossRef]
17. Rassõlkin, A.; Vaimann, T.; Kallaste, A.; Kuts, V. Digital twin for propulsion drive of autonomous electric vehicle. In Proceedings of the 2019 IEEE 60th International Scientific Conference on Power and Electrical Engineering of Riga Technical University (RTUCON), Riga, Latvia, 7–9 October 2019; pp. 1–4. [CrossRef]
18. Liu, Y.; Tu, X.; Chen, D.; Han, K.; Altintas, O.; Wang, H.; Xie, J. Visualization of Mobility Digital Twin: Framework Design, Case Study, and Future Challenges. In Proceedings of the 2023 IEEE 20th International Conference on Mobile Ad Hoc and Smart System (MASS), Toronto, ON, Canada, 25–27 September 2023.
19. Lima, V.L. Articulação Entre Mobilidade Urbana e Meio Ambiente em Projetos Urbanos: Potencialidade de Redução de Mudanças Climáticas nos Projetos da Operação Urbana Rio Verde-Jacu. In Proceedings of the XIV SIIU Seminário Internacional de Investigação em Urbanismo, Madrid, Spain, 23–24 June 2022. [CrossRef]
20. Tabora, J.M.; Paixão Júnior, U.C.; Rodrigues, C.E.M.; Bezerra, U.H.; Tostes, M.E.d.L.; de Albuquerque, B.S.; de Matos, E.O.; de Nascimento, A.A. Hybrid System Assessment in On-Grid and Off-Grid Conditions: A Technical and Economical Approach. *Energies* **2021**, *14*, 5284. [CrossRef]
21. Gryparis, E.; Papadopoulos, P.; Leligou, H.C.; Psomopoulos, C.S. Electricity demand and carbon emission in power generation under high penetration of electric vehicles. A European Union perspective. *Energy Rep.* **2020**, *6*, 475–486. [CrossRef]
22. Leal Filho, W.; Abubakar, I.R.; Kotter, R.; Grindsted, T.S.; Balogun, A.L.; Salvia, A.L.; Aina, Y.A.; Wolf, F. Framing Electric Mobility for Urban Sustainability in a Circular Economy Context: An Overview of the Literature. *Sustainability* **2021**, *13*, 7786. [CrossRef]
23. Tang, C.; Tukker, A.; Sprecher, B.; Mogollon, J.M. Assessing the European Electric-Mobility Transition: Emissions from Electric Vehicle Manufacturing and Use in Relation to the EU Greenhouse Gas Emission Targets. *Environ. Sci. Technol.* **2022**, *57*, 44–52. [CrossRef] [PubMed]
24. Cancela, A.; Lastra, R.; Suárez, V.; Sánchez, A. Design and Simulation of a Sustainable Photovoltaic Electric Plug-In Boat. *Eur. J. Sustain. Dev.* **2016**, *5*, 325.
25. Borges, L.S.; Nobre, J.C.A.; Sousa, D.L.P.; Andrade, L.C.F. Construction of a new solar radiation profile and air temperature from known weather patterns for the city of Belém-PA. *J. Eng. Exact Sci.* **2023**, *9*. [CrossRef]
26. Nikmatullah, M.I.; Baharuddin, B.; Zulkifli, Z.; Alwi, M.R.; Sitepu, A.H. Modification of Traditional Fishing Boat Outriggers into a Simple Electric Power Plant. *Indones. J. Marit. Technol.* **2023**, *1*, 65–70. [CrossRef]
27. Hasan, T.; Jamaludin, S.; Nik, W.B.; Rajib, M.H. Study and Analysis of a Solar Electric Boat with Dynamic Design Strategy in Efficient Way. In Proceedings of the 13th International Conference on Marine Technology (MARTEC 2022), Dhaka, Bangladesh, 21–22 December 2022. [CrossRef]

28. Namuduri, K. Digital Twin Approach for Integrated Airspace Management with Applications to Advanced Air Mobility. *IEEE Open J. Veh. Technol.* **2023**, *4*, 693–700. [CrossRef]
29. Rahman, T.; Alharbi, T. Exploring Lithium-Ion Battery Degradation: A Concise Review of Critical Factors, Impacts, Data-Driven Degradation Estimation Techniques, and Sustainable Directions for Energy Storage Systems. *Batteries* **2024**, *10*, 220. [CrossRef]
30. DETIC Unicamp. Available online: https://www.detic.unicamp.br/softwares/matlab-2 (accessed on 27 July 2024).
31. Instituto Politécnico de Bragança. Introdução ao Simulink. Available online: https://www.ipb.pt/~jpcoelho/CCD/documento.pdf (accessed on 27 July 2024).
32. Ibbini, M.S.; Mansi, S.; Masadeh, M.A.; Hajri, E.A. Simscape Solar Cells Model Analysis and Design. *Comput. Appl. Environ. Sci. Renew. Energy* **2014**, 97–103.
33. Santos, W.J.P.; Albuquerque, B.S.; Nascimento, A.L.L.; Couto, G.A.S.; Carvalho, C.C.M.; Tostes, M.E.L.; Nascimento, A.A. Análise de Desempenho com Auxílio de Termograia: Estudo de Caso do Mirante do Rio. In Proceedings of the XIV Latin-American Congress on Electricity Generation and Transmission—CLAGTEE 2022, Rio de Janeiro, Brazil, 29 November–1 December 2022.
34. Yadav, P.; Kumar, N.; Chandel, S.S. Simulation and performance analysis of a 1kWp photovoltaic system using PVsyst. In Proceedings of the 2015 International Conference on Computation of Power, Energy Information and Communication (ICCPEIC), Melmaruvathur, India, 22–23 April 2015.
35. Norte Energia. Available online: https://www.norteenergiasa.com.br/pt-br/ped/projetos-de-ped-em-curso/mobilidade-eletrica (accessed on 30 September 2022).
36. Nascimento, A.L.L.; Albuquerque, B.S.; Rozal Filho, E.O.; Jorge, L.R.M.; Carvalho, C.C.M.M.; Tostes, M.E.L. Estimativa de payback de um sistema fotovoltaico híbrido para um prédio público educacional. In Proceedings of the 2023 XV Brazilian Conference on Quality of Power (CBQEE), São Luiz, Brazil, 4–6 September 2023; pp. 1–6. [CrossRef]