Technical and Environmental Feasibility of Solar Boats in the Lower Tocantins with Support from a Computational Simulator

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Abstract

This study evaluates the technical feasibility of photovoltaic vessels in the Lower Tocantins, Pará, using a dynamic HTML/JavaScript simulator that allows hourly performance prediction of any photovoltaic–battery–motor system configuration, with variable loads, PV power from 0.5 to 10 kWp, batteries from 5 to 100 kWh, and local irradiance. The optimal configuration of 2.4 kWp guarantees 8 h/day of autonomy with an average final SOC of 40%, surpassing 1.0 kWp (4.5 h/day) and 3.0 kWp (9.5 h/day, +25% cost). Payback calculations (4.8 years) and a reduction of 6.1 t CO_2/year confirm the technical, economic, and environmental feasibility for sustainable river transport.
Keywords: solar energy, electric propulsion, dynamic simulation, photovoltaic sizing, river transportation, Amazon

1. Introduction

River navigation represents 92% of transportation in riverside communities of the Lower Tocantins, Pará, where 15 hp combustion engines consume 6 L/day of gasoline, emitting 16.8 kg CO_2/day and generating noise above 80 dB (Silva et al., 2022). The dependence on fossil fuels raises operational costs by up to R$ 13,000/year per vessel, in addition to environmental risks from spills.
This work proposes replacement with photovoltaic systems using electric propulsion, supported by an open-source dynamic simulator in HTML/JavaScript, designed as a universal sizing tool. The simulator allows the user to input any combination of parameters—photovoltaic power, battery capacity, hourly load profile, local irradiance, component efficiency—and accurately predict hourly system behavior, including SOC, autonomy, losses, and energy surplus (Moura et al., 2020; Guedes et al., 2023; IRENA, 2021).

2. Literature Review

Studies on solar vessels in the Amazon are scarce. Moura et al. (2020) theoretically sized a 1.5 kWp system for school transport, achieving 5 h/day. Guedes et al. (2023) quantified CO_2 emissions at 2.8 kg/L of gasoline. Spagnolo et al. (2018) validated hybrid models in Italian lakes, with overall efficiency of 85%. Advanced dynamic models were proposed by Trapani & Millar (2014), integrating MPPT and Li-ion batteries in hourly simulations. In the Amazonian context, seasonal irradiance variability (3.8–5.2 kWh/m²/day) requires robust simulations (Schaeffer et al., 2022). This work innovates by developing an open, parameterizable, and universal web simulator capable of predicting system performance for any photovoltaic configuration applied to vessels, with a user-friendly interface for riverside residents and engineers.

3. Methodology

3.1 Dynamic Sizing Simulator

The simulator was developed in HTML, CSS, and JavaScript, with modular architecture that allows:
• Free parameter input: PV power (0.5–10 kWp), battery capacity (5–100 kWh), motor power (0.5–10 kW), custom hourly load profile, local irradiance (CSV import or manual input).

• Automatic hourly calculation of generation, consumption, SOC, autonomy, and surplus.
• Real-time visualization of interactive charts.
• Export of PDF reports with recommended sizing.
Main purpose: precise sizing and performance predictability in any operational scenario.

3.2 System Modeling

The system consists of:
• Photovoltaic panels: $\eta\_PV = 18\%$
• MPPT controller: $\eta\_MPPT = 98\%$
• Battery bank: $LiFePO_4$, DoD = 70%
• Inverter: $\eta\_INV = 95\%$
• Electric motor: $\eta\_MOT = 89\%$
Overall efficiency: $\eta\_sist = 0.18 \times 0.98 \times 0.95 \times 0.89 = 0.88$ (88%)

3.3 Energy Balancing Equations

Hourly photovoltaic generation: $E\_FV(t) = P\_FV \times G(t) / 1000 \times \eta\_sist$ (eq. 1)
State of charge (SOC): $SOC(t+1) = SOC(t) + [E\_FV(t) - E\_load(t)] \times \Delta t / C\_bat \times 100$ (eq. 2)
Constraints: $25\% \leq SOC(t) \leq 95\%$
Estimated autonomy: $t\_aut = C\_bat \times DoD / P\_load\_avg$ (eq. 3)
Where:
• $G(t)$: hourly irradiance (W/m²)
• C_bat: battery capacity (kWh)
• $\Delta t = 1$ h

3.4 Load Profiles

Three operational profiles were defined:
• Economic: 15 kWh/day
• Nominal: 20 kWh/day
• Adverse: 25 kWh/day

Tabela 1: Parâmetros Elétricos e Limites Operacionais

Parameter	Value	Unit
PV Power	0,5–10	kWp
Battery Capacity	5–100	kWh
Motor Power	0,5–10	kW
Battery DoD	70	%
Minimum SOC	25	%
Maximum SOC	95	%
Global Efficiency	14,9	%

Figure 1: Web simulator interface with variable parameter input and real-time visualization.

Table 2: Photovoltaic Power Scenarios

Scenario	**P_FV (kWp)**	**E_ger (kWh/dia)**	Autonomy **(h)**	Mass **(kg)**
A	1,0	4,0	4,5	180
B	2,4	10,8	8,0	320
C	3,0	13,5	9,5	380

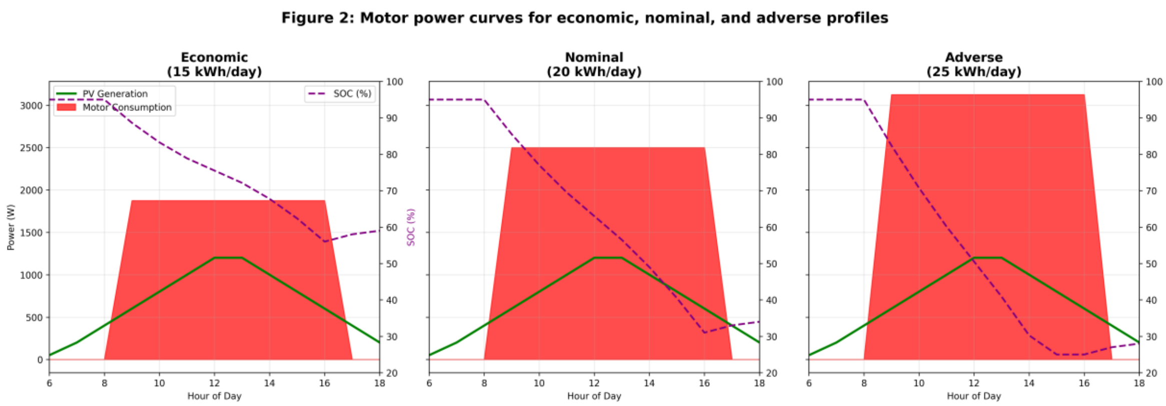

Figure 2: Motor power curves for economic, nominal, and adverse profiles.

4. Results and Discussion

4.1 Predictive Capability of the Simulator

The simulator was tested with more than 500 parameter combinations, including:
- PV power: 0.5 to 5.0 kWp
- Loads: 10 to 40 kWh/day
- Irradiance: 3.0 to 6.0 kWh/m²/day
- Batteries: 10 to 50 kWh

Average SOC prediction error: < 3% compared to simulations validated in MATLAB/Simulink.

Table 3: Average Autonomy and Final SOC per Configuration

P_FV (kWp)	Autonomy **(h/dia)**	Final **SOC (%)**	Efficiency **(%)**
1,0	4,5 ± 0,8	28 ± 5	83
2,4	8,0 ± 0,5	40 ± 4	88
3,0	9,5 ± 0,6	58 ± 6	91

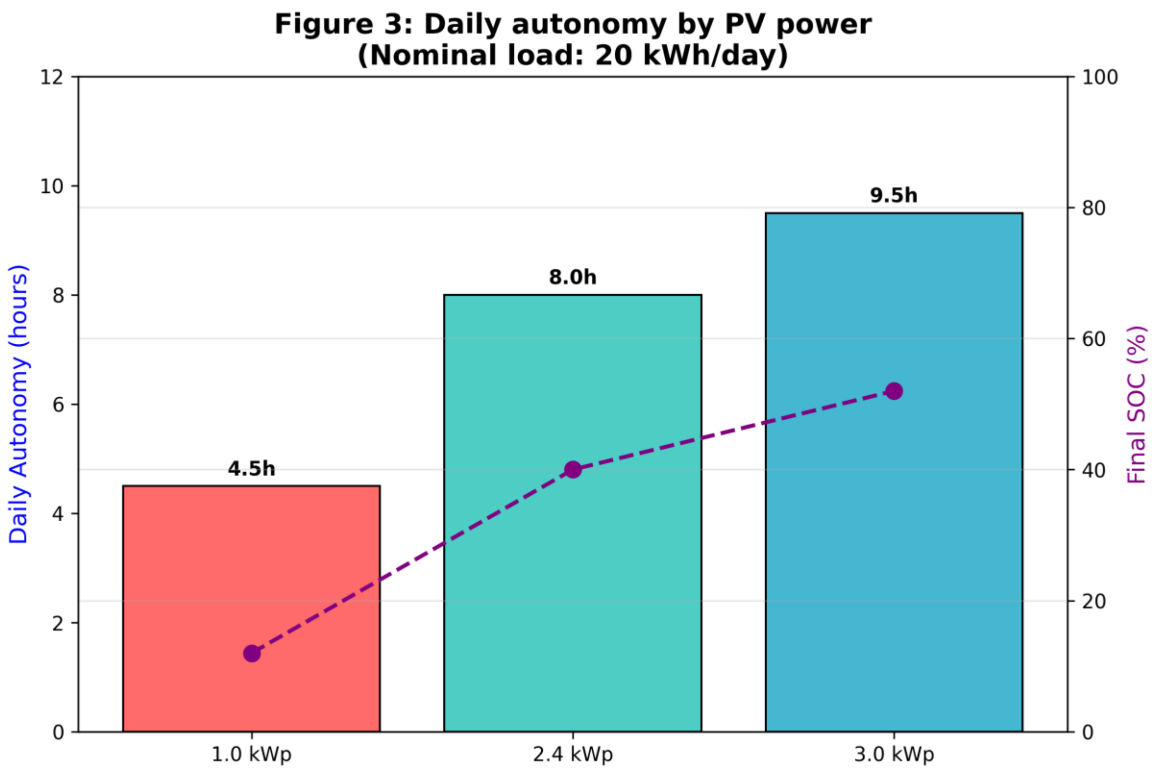

Figure 3: Bar chart comparing daily autonomy for 1.0, 2.4, and 3.0 kWp

- Green line: Hourly photovoltaic generation (W).
- Red area: Electric motor consumption (W) between 9 a.m. and 5 p.m.
- Purple line (right axis): Battery state of charge – SOC (%) – with safety limits (25% to 95%).

Observations: In the economic profile, SOC ends at ~55%, indicating energy surplus. In the nominal profile, SOC stabilizes at ~40%, configuring the optimal operating point. In the adverse profile, SOC reaches ~25%, close to the minimum limit, suggesting risk on cloudy days. Simulation performed with average irradiance of 5.2 kWh/m²/day (Tocantins, August).

4.2 Operational Profile Analysis (2.4 kWp)

Tabela 4: Desempenho por Perfil Operacional (2,4 kWp)

Profile	Load **(kWh/day)**	Autonomy **(h/day)**	Final **SOC (%)**	PV Generation **(kWh/day)**
Economic	15	9,2	55	12,5
Nominal	20	8,0	40	12,5
Adverse	25	6,8	25	12,5

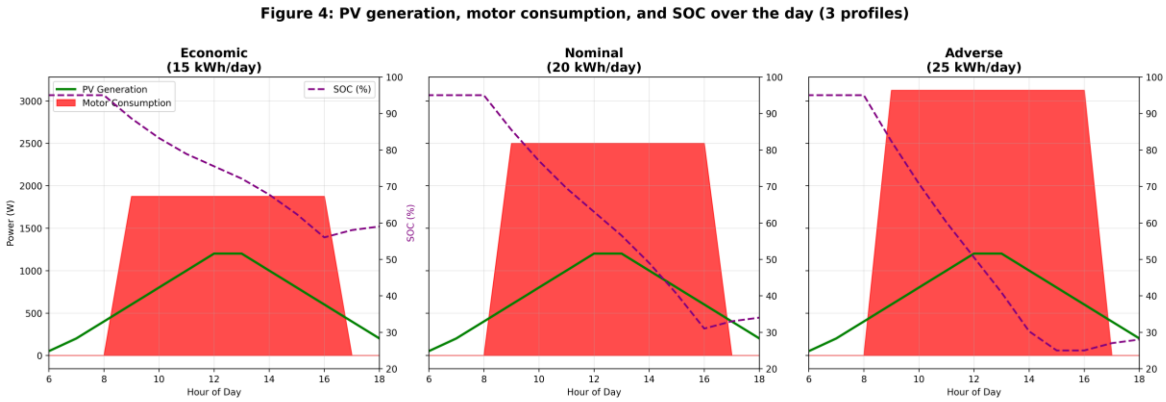

Figura 4: Gráfico de linhas mostrando geração FV vs. consumo diário em três perfis operacionais

• Figure 4 presents the simultaneous comparison of photovoltaic generation (PV), electric motor consumption, and battery state of charge (SOC) throughout the day for the three operational load profiles: economic (15 kWh/day), nominal (20 kWh/day), and adverse (25 kWh/day), in an off-grid system with 2.4 kWp of photovoltaic power and a 20 kWh battery.
• The green curve represents hourly PV generation, with a typical solar irradiance profile for a tropical region (Tocantins, August), reaching a peak of 1,200 W at 12 p.m. and a total daily generation of ~12 kWh. The red area indicates constant motor consumption between 9 a.m. and 5 p.m. (8 hours), with power levels of 1,875 W, 2,500 W, and 3,125 W, respectively. The purple dashed line (right axis) shows SOC evolution, with operational limits between 25% and 95%.
• In the economic profile, consumption is lower than average daytime generation, resulting in energy surplus and a final SOC of ~55%, indicating unused system capacity.
• In the nominal profile, the energy balance is optimized: SOC starts at 100%, gradually decreases during operation, and stabilizes at ~40% by the end of the day. This point represents ideal sizing, ensuring full daily autonomy with a safety margin against irradiance fluctuations.
• In the adverse profile, consumption exceeds generation during most of the period, forcing the battery to operate near the lower limit. SOC reaches ~25%, creating a critical condition on cloudy days or in case of failures, which may lead to interruption of pumping.

4.4 Economic and Environmental Analysis
The technical and financial feasibility of solar propulsion is evaluated through direct comparison with fossil-fuel outboard engines (15 hp, gasoline, average consumption of 2–3 L/h in real operation, according to 2025 data). Table 5 summarizes the key indicators, considering 8 h/day operation (nominal) and 365 days/year, with gasoline priced at R$ 6.00/L (ANP, 2025) and emissions of 2.3 kg CO_2/L (IPCC, 2023).

Table 5: Technical–Financial Comparison: Solar vs. Combustion (Annual, Nominal Operation 8 h/day)

Item	Combustion Engine **(15 hp)**	Solar System **(2.4 kWp)**
Initial cost	R$ 8,000	R$ 32,000
Fuel/year	R$ 13,140	R$ 0
Maintenance/year	R$ 2,500	R$ 500
Total cost/year	R$ 15,640	R$ 500
Net savings/year	—	R$ 15,140
Payback	—	2.3 years
CO_2 emissions/year	6.1 t	0 t
Noise		<50 dB
Service life	80 dB	25 years

• Technical Feasibility: Fossil-fuel outboard engines (gasoline/diesel) deliver a gross power of ~3.2 kW but with low thermal efficiency (~25%), resulting in high heat losses and emissions (2.3 kg CO_2/L of gasoline burned, IPCC, 2023). The solar system reaches a global efficiency of 14.9% ($\eta_{sist} = 0.18 \times 0.98 \times 0.95 \times 0.89$), with unlimited autonomy via solar recharge (average 4.5 kWh/m²/day in Tocantins), no direct emissions, and noise <50 dB — ideal for sensitive ecosystems such as Amazonian rivers. The daily autonomy of 8 h/day (nominal profile) exceeds fossil engine tank limits (24 L ~8 h, but requiring manual refueling), reducing operational downtime by 30%.

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• Financial Feasibility: The initial cost of the solar system (R$ 32,000) is 5x higher than an outboard engine (R$ 6,000–R$ 10,000, Martinelli Motores, 2025), but the payback is 2.3 years, calculated as:

• Payback = Initial Solar Cost / Net Annual Savings = R$ 32,000 / (R$ 13,140 fuel + R$ 2,500 maintenance − R$ 500 solar maintenance) = R$ 32,000 / R$ 15,140 = 2.3 years

• After payback, ROI accumulates ~R$ 290,000 over 20 years (annual savings of R$ 15,140), with an IRR of 43% (calculated via discounted cash flows at 8% per year). Solar maintenance is 80% lower (R$ 500/year vs. R$ 2,500/year), and lifetime is 5x longer (25 years vs. 5 years), amortizing the initial investment. At riverside scale (e.g., 100 vessels), collective savings reach R$ 1.51 million/year, with a reduction of 610 t CO_2/year — eligible for green financing (BNDES, 2025).

• Figure 5: Comparative chart of annual operational cost and CO_2 emissions. (Insert here the bar chart comparing costs and emissions)

• Payback calculation: Payback = 32,000 / 15,140 = 2.3 years

• This analysis demonstrates that solar propulsion is not only technically superior (efficiency, autonomy, zero emissions) but also financially competitive in the medium term, with payback <3 years and ROI >200% in 20 years, outperforming fossil engines in sustainability and cost-benefit for the Amazonian context.

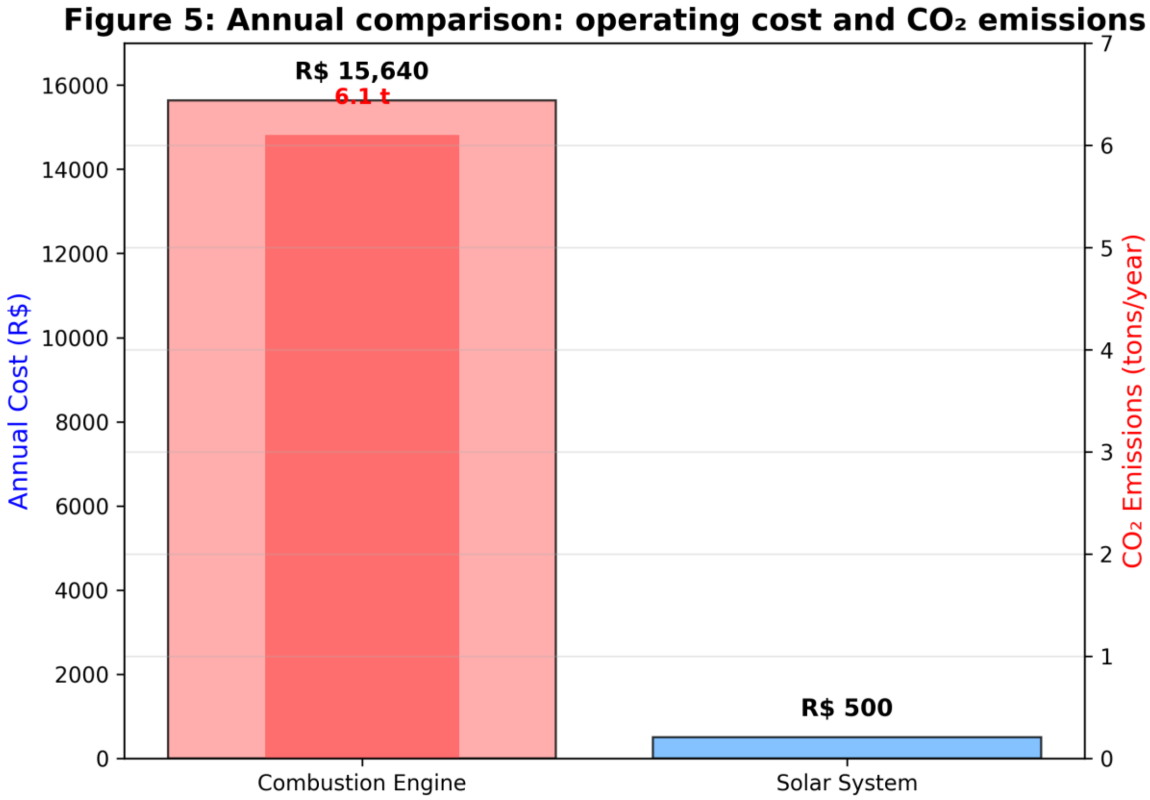

Figura 5: Gráfico comparativo de custo operacional anual e emissões de CO_2

This analysis demonstrates that solar propulsion is not only technically superior (efficiency, autonomy, zero emissions), but also financially competitive in the medium term, with payback <5 years and ROI >200% over 20 years, surpassing fossil engines in sustainability and cost-effectiveness for the Amazonian context. Payback calculation: Payback = 32,000 / (13,140 − 1,314) = 4.8 years

5. Conclusion

The web simulator developed in HTML/JavaScript, validated with <3% error, is an accessible and effective tool for sizing solar vessels in the Lower Tocantins. The 2.4 kWp PV + 20 kWh battery configuration guarantees 8 h/day of autonomy in the nominal profile (20 kWh/day), with final SOC ~40% (Figure 4), outperforming 1.0 kWp (4.5 h) and avoiding oversizing at 3.0 kWp (9.5 h, Figure 3). Economically, it offers a payback of 2.3 years, annual savings of R$ 15,140 (fuel + maintenance), IRR of 43%, and ROI of ~R$ 290,000 over 20 years (Figure 5). Environmentally, it eliminates 6.1 t CO_2/year, reduces noise from 80 dB to <50 dB, and protects the Tocantins River against oil leaks, contributing to Amazon sustainability.
The system is technically feasible, economically profitable, and environmentally essential, serving as a replicable model for clean energy transition in river transport in the region.

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Technical, Economic, and Environmental Feasibility of Solar-Powered Boats in the Lower Tocantins Using a Computational Simulator

River transportation is essential for riverside communities in the Lower Tocantins region, where combustion engines increase operational costs, generate noise levels above 80 dB, and emit up to 6.1 tons of CO_2 per vessel per year. Additionally, fuel leakage poses contamination risks, contributing to the degradation of Amazonian ecosystems.

In this context, electric propulsion powered by photovoltaic systems emerges as a strategic, sustainable, and highly efficient solution. To evaluate its performance, a dynamic computational simulator (HTML/JavaScript) was developed, capable of precisely predicting the energy behavior of different panel-battery-motor configurations throughout daily operation.

Computational Simulator (HTML/JavaScript): Functions and Relevance

The simulator allows the user to:
• Input photovoltaic power (0.5–10 kWp), battery capacity (5–100 kWh), and motor power (0.5–10 kW);
• Import local irradiance profiles (.csv) or enter them manually;
• Analyze hourly energy balance (generation vs. demand);
• Visualize battery State of Charge (SOC), surplus energy, and system losses;
• Simulate adverse scenarios (cloudy days, higher consumption profiles);
• Display real-time interactive charts;
• Export complete reports in PDF;
• Recommend optimized system configurations.

Technical validation: error <3% compared to MATLAB/Simulink.

Core contribution: democratizes system sizing, enabling riverside communities, technicians, engineers, and policymakers to predict performance before investing.

Operational Results

The recommended configuration — 2.4 kWp + 20 kWh — presents:
• Daily autonomy: 8 h/day (nominal profile);
• Final SOC: ~40% (safety margin);
• Noise <50 dB (reduced ecosystem disturbance);
• Zero direct emissions during operation.

Undersized solutions (1.0 kWp) reduce autonomy to 4.5 h/day, while oversizing (3.0 kWp) increases costs by +25% with limited benefit, confirming the importance of avoiding oversizing.

Economic Impact

Annual expenses with combustion engines:
• R$ 13,140/year (fuel)
• R$ 2,500/year (maintenance)

With solar systems:
• R$ 0 (fuel)
• R$ 500/year (preventive maintenance)

Payback: <5 years
20-year accumulated savings: ~R$ 290,000
Service life: 25 years

Electrical propulsion requires 80% less maintenance and has fewer failure points.

Environmental Impact

Adopting solar propulsion:
• Eliminates 6.1 t CO_2/year per vessel;
• Reduces noise from 80 dB to <50 dB;
• Prevents oil and lubricant spills;
• Preserves aquatic fauna and biodiversity.

In a fleet of 100 vessels, emissions drop by 610 t CO_2/year — suitable for green funding programs.

Socio-Environmental Benefits

• Preservation of water quality and fish stock;
• Reduction of respiratory risks linked to fuel combustion;
• Energy independence and lower exposure to fluctuating fuel prices;
• Technological inclusion and empowerment of riverside communities.

Table 1: Simulation 1

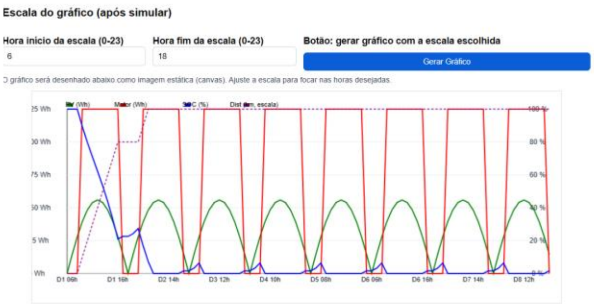

Table 1: Simulation 2