

Article

Sustainable Hybrid Off-Grid Energy Systems for Rural Electrification in the Amazon Region

Thiago José da Luz ^{1,*}, Andre de Souza Leone ¹, Édwin Augusto Tonolo ¹, Marcos Vinicio Haas Rambo ^{1,2}, João Carlos Jachenski Junior ^{1,2}, Fabiana de Marqui Mantovan ^{3,4}, Taciano Ares Rodolfo ³, Paulo Smith Schneider ^{3,4} and Bruno Knevez Hammerschmitt ^{5,*}

¹ Future Grid, Lactec, Curitiba 80215-090, Paraná, Brazil; andre.leone@lactec.com.br (A.d.S.L.); edwin.tonolo@lactec.com.br (É.A.T.); marcos.rambo@lactec.com.br (M.V.H.R.); joao.junior@lactec.com.br (J.C.J.J.)

² Department of Electrical Engineering, Federal University of Paraná, Curitiba 81531-980, Paraná, Brazil

³ Center for Embedded Devices and Research in Digital Agriculture (CEDRA) of SENAI-RS, São Leopoldo 93025-753, Rio Grande do Sul, Brazil; fabiana.marqui22@gmail.com (F.d.M.M.); taciano.rodolfo@senairs.org.br (T.A.R.); xdr.paulo@gmail.com (P.S.S.)

⁴ Mechanical Engineering, Federal University of Rio Grande Do Sul (UFRGS), Porto Alegre 90040-060, Rio Grande do Sul, Brazil

⁵ Department of Electronics, Federal University of Technology—Paraná, Ponta Grossa 84017-220, Paraná, Brazil

* Correspondence: thiago.luz@lactec.com.br (T.J.d.L.); brunok@utfpr.edu.br (B.K.H.)

Abstract

Although Brazil is in the last mile of achieving universal electricity access, the Amazon region represents the country's most critical electrification frontier, where remote energy expansion has largely failed to integrate clean alternatives. This study presents the design and techno-economic assessment of a hybrid off-grid microgrid tailored for the Amazon, incorporating a multi-source architecture that combines micro-hydro (MH), wind power (WT), solar photovoltaics (PV), diesel generation (DG), and battery energy storage systems (BESS). Three locations in Amazonas, Roraima, and Tocantins were evaluated under three scenarios: a hybrid system with DG, a fully renewable system without DG, and a green scenario that accounts for demand-side flexibility and selected technical and economic conditions. Optimization was performed using the HOMER tool for a typical isolated community. The hybrid configuration achieved a DG generation share of 0.7 (RSS, DG-WT-PV-MH-BESS), 0.9% (Jalapão, DG-WT-PV-MH-BESS), and 6.8% (Labrea, DG-PV-BESS). The fully renewable scenario resulted in Levelized Cost of Energy (COE) values ranging from 0.146 USD/kWh (RSS) to 0.388 USD/kWh (Lábrea), while the green scenario yielded COEs between 0.089 USD/kWh (RSS) and 0.190 USD/kWh (Lábrea). This study reveals the role of MH in reducing storage requirements, installed capacity, and system cost. The results are promising for presenting a competitive cost of energy.

Keywords: hybrid system; microgrid; rural electrification; Amazon region; optimization tool; renewable energy integration

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1. Introduction

According to the International Energy Agency (IEA) [1], approximately 8% of the global population still lacks access to electricity, corresponding to about 655 million people. Sustainable Development Goal 7 (SDG 7) aims to ensure access to affordable, reliable,

sustainable, and modern energy for all, while Target 7.1 specifically addresses universal access to affordable, reliable, and modern energy services. The IEA also reports that progress in electrification has been uneven among remote populations, women, residents of informal settlements, and indigenous communities. The remaining access gap is increasingly concentrated in rural and geographically isolated areas, where infrastructure limitations continue to restrict conventional electrification. Indigenous communities are among the populations that still face persistent barriers to electricity access, reinforcing the challenge of achieving universal access by 2030 [1].

There are successful electrification programs worldwide. However, the remaining electrification challenge differs from earlier national-scale expansion programs because populations without access are increasingly concentrated in dispersed and difficult-to-reach areas. Recent studies have therefore focused on decentralized generation and hybrid renewable energy systems (HRES) adapted to local resource availability and demand profiles [2–4].

The challenge remains particularly pronounced in Sub-Saharan Africa, where approximately 563 million people still lack access to electricity [1]. Rural populations account for a large share of those who remain without electricity access [1]. As a consequence, these regions often present low educational attainment, marked gender disparities, limited access to healthcare services, basic infrastructure, and safe water, while local livelihoods frequently depend on activities such as pastoralism, livestock production, agriculture, fishing, tourism, and forestry [5]. Electrification, in turn, can contribute to reducing poverty, stimulating rural economic activity, improving health, education, and quality of life, limiting migration pressures, lowering household expenditures, reducing rural–urban inequalities, and supporting environmental sustainability [5]. In agricultural communities, electricity access also supports productive activities such as irrigation, lighting, water supply, and agro-processing, linking rural electrification directly to local economic development [6].

Grid extension is generally considered the primary electrification option; however, in rural areas, low electricity demand and dispersed settlements can make network expansion technically and economically unfeasible [7]. A review of rural electrification in developing countries presents off-grid small-scale electricity generation as one of the most appropriate options for last-mile electricity access [8]. Studies confirm that isolated and geographically constrained regions continue to rely on decentralized systems when conventional interconnection is technically or economically difficult [2–4].

Remote communities have traditionally relied on diesel generators (DG) because they provide dispatchable power independently of local renewable resource availability. However, fuel transportation and operation increase the cost of energy (COE) in isolated areas, which has encouraged the adoption of HRES [2]. Among the available technologies, photovoltaic (PV) generation is frequently used in standalone applications due to its modularity and ease of deployment. Because solar production is intermittent, PV systems are commonly integrated with Battery Energy Storage Systems (BESS) to maintain electricity supply during periods of low or absent solar generation [9].

In microgrids, PV and micro-hydro (MH) systems are commonly adopted renewable options [8]. However, the feasibility of MH systems is strongly site-dependent, as their implementation requires adequate water flow and hydraulic head [10]. Some studies also indicate that the selection of renewable sources should follow local resource availability and temporal complementarity. In [3], PV and hydrokinetic generation were combined under seasonal resource conditions, whereas in [11], solar and wind generation integrated with battery and pumped-hydro storage was evaluated.

The PV–DG hybrid system has complementarity characteristics and several advantages, such as reduced battery requirements, lower emissions, and lower COE [9], or

the storage requirement can be supplied by pumped-hydro storage [11]. Some authors also present wind turbine (WT) systems, hydrogen storage, biomass, fuel cells, and combinations of different storage technologies as alternatives whose suitability depends on resource availability, system scale, and operational requirements [2,12].

The design of hybrid systems involves multiple technical and economic variables, making computational tools and models important for supporting decision-making. In general, the optimization process seeks a system configuration that meets electricity demand at the lowest possible cost. Current optimization approaches extend this objective by incorporating reliability, environmental performance, resilience, and, in some cases, social criteria in multi-objective formulations [13].

In this context, previous reviews have compared the capabilities, advantages, and limitations of different tools used for hybrid system analysis, including HOMER, Hybrid2, and iHOGA, and have identified HOMER as one of the most widely adopted platforms in this field [9,14]. In ref. [14], optimization approaches for hybrid microgrids were classified into classical, metaheuristic, and artificial-intelligence-based methods, while HOMER and MATLAB/Simulink were identified as the most frequently used modeling tools. More recently, ref. [15] used HOMER-generated scenarios to train machine-learning surrogate models for rapid sizing of PV, inverter, and battery capacities, illustrating the increasing integration of data-driven methods into renewable-system design.

Rural Electrification Challenge

According to the National Electric System Operator (Operador Nacional do Sistema Elétrico, ONS), Brazil has 160 isolated electricity systems, corresponding to 3.761 TWh and approximately 0.5% of national electricity demand. About 70% of this energy supply comes from local thermal generation using diesel fuel [16]. As shown in Figure 1, these systems are predominantly located in the Legal Amazon, with 78% concentrated in Amazonas and Roraima, where the marked points represent the various electrical distribution utilities serving the region [16].



Figure 1. Isolated electrical systems in Brazil, where colored dots indicate the distribution utilities serving isolated communities across the Legal Amazon [16].

In recent decades, the Light for All program has promoted access to energy for 16.9 million Brazilians. The program started in 2003, and in twenty years, it has already benefited 17.2 million people [17]. However, according to the last demographic census, the estimated number of Brazilians without continuous access to energy is 3 million [18]. At the national level, the remaining electricity-access challenge is increasingly associated with remote and geographically isolated populations, a pattern also observed across Latin America [1].

In response to the specific challenges of remote communities in the Legal Amazon, the Brazilian government established the More Light for the Amazon (Mais Luz para a Amazônia, MLA) program to expand electricity access while supporting the social and economic development of these populations [19]. The program also linked electrification to income-generating activities and the sustainable use of local natural resources [19].

Although the Amazon region has considerable biomass and hydropower resources, electricity supply in isolated communities still relies heavily on diesel-based generation [16]. In 2025, DG accounted for approximately 70% of the electricity generated in the Brazilian Isolated Systems (Sistemas Isolados, SISOL). According to the Energy Research Office (Empresa de Pesquisa Energética, EPE), SISOL emissions reached approximately 2.50 MtCO₂eq, with an average emission intensity of 0.67 tCO₂/MWh, considerably higher than that associated with the Brazilian interconnected system [16].

Typically, thermal plants used in remote areas are small DG with capacities between 10 and 100 kW, used to deliver precarious electricity and satisfy the energy demand for a few hours of night lighting (typically 18:00 to 22:00) in inefficient engines [20,21]. Nevertheless, the current SISOL comprises systems with markedly different scales and load profiles, and its characterization should not be restricted to small generators supplying only nighttime demand [16].

Diesel-based electricity supply in isolated communities is also associated with higher greenhouse gas emissions than electricity supplied through the interconnected system. This difference is partly explained by the highly renewable profile of the Brazilian electricity mix, which has historically been dominated by hydropower and has increasingly incorporated wind and solar generation. In addition, inadequate handling and disposal of diesel fuel may lead to contamination of rivers and soils near residential areas, increasing environmental pressures on sensitive Amazonian ecosystems [22]. Nevertheless, diesel-based systems remain attractive because of their relatively low initial investment, established maintenance and operational practices, and the tax revenues associated with fuel consumption [23,24]. Similar reliance on DG is observed in other isolated regions, where hybrid configurations integrating PV, WT, and BESS have been investigated to reduce both fuel consumption and dependence on diesel supply logistics [2,12].

Small-scale off-grid electrification initiatives have been implemented in the Brazilian Amazon for more than two decades, with participation from public institutions, non-governmental organizations, utilities, and local communities [25]. The authors of [26] reviewed experimental microgrid projects in the region and reported the use of run-of-river hydropower, hydrokinetic systems, biomass, biofuels, and hybrid PV–WT–DG configurations. In the same order, ref. [7] also identified projects based on PV, DG, MH, thermal biomass, and hybrid WT–DG and WT–PV–DG systems. Other technological pathways have included biodigesters and biomass gasification [20], a PV–fuel cell–BESS configuration [27], and a PV–MH–BESS microgrid proposed as an alternative to diesel-based generation [28]. Finally, ref. [29] evaluated a PV–DG–BESS system in which the diesel contribution was reduced to 14.4%.

More recent studies in regions with comparable electrification constraints have expanded this approach toward resource-specific hybridization. In ref. [4], PV generation and hybrid renewable integration were evaluated in the Ecuadorian Amazon, whereas in

ref. [3], PV–hydrokinetic microgrids were investigated for isolated communities in the Colombian Pacific. These studies reinforce the role of local resource characterization when selecting generation and storage technologies for remote systems.

However, WT was not considered in these studies. Although wind resources are limited across most of the Amazon region [29], technically exploitable conditions have been reported in northern Roraima and along the coastal areas of Pará and Amapá [30]. Hydropower has likewise received comparatively limited attention in the region, despite its considerable local potential. The combined assessment of these resources is relevant because complementarity among solar, wind, and hydropower can alter both the required storage capacity and the dispatch of backup generation. Recent studies on HRES increasingly formulate source selection, component sizing, storage capacity, and operational strategies as interdependent optimization decisions rather than as separate design stages [9,13].

Although Brazil is approaching universal electricity access, the expansion of supply in isolated areas has not necessarily been based on low-carbon generation. In this context, electrification policies for remote areas have increasingly incorporated broader development objectives. The MLA explicitly associates electricity access in the Legal Amazon with social and economic development, income-generating activities, and the sustainable use of local natural resources [19]. Current planning for SISOL also reflects this broader perspective by considering hybrid configurations that combine thermal generation with renewable sources and energy storage, thereby addressing not only electricity access but also cost, fuel dependence, and emissions [16].

Comparative assessments of hybrid system configurations across locations with different resource conditions remain limited in the Amazon region. In particular, relatively few studies have examined the contribution of WT and MH within these systems. Although HRES optimization is now widely addressed in the international literature, including multi-objective optimization for agricultural and rural applications [6] and combinations of renewable generation with batteries and hydrogen storage [12], comparative analyses applying a common framework to Amazonian locations with distinct solar, wind, and hydrological resources remain limited.

Therefore, this paper extends our previous work on hybrid microgrid design for the Brazilian Amazon [31] through a techno-economic and environmental assessment performed using HOMER Pro. Three isolated locations, each representing a community of 50 households and distinct renewable resource conditions within the Legal Amazon, were evaluated. The analysis was structured into three scenarios:

- Hybrid microgrid with DG, to evaluate renewable integration while maintaining dispatchable generation as a backup source;
- HRES to assess the feasibility and system requirements associated with eliminating DG from the generation mix; and
- The green scenario, to investigate the effects of demand flexibility together with selected technical and economic sensitivity conditions on the resulting renewable configuration.

The main contribution of this study lies in extending the previous analysis through a different modeling framework and a broader assessment of alternative microgrid configurations. While the previous work focused on the development of Benders Decomposition (BD) and rolling horizon (RH) optimization approaches, the present study employs HOMER Pro [32] to evaluate multiple system configurations and scenarios under a common simulation framework. The HOMER-based approach also enables sensitivity analyses and accounts for battery lifetime and degradation-related effects through storage lifetime and energy-throughput constraints. This framework is used to examine how the availability and complementarity of PV, WT, and MH influence system composition, BESS requirements, diesel dependence, excess electricity production, and COE. The effect of

Demand Response (DR) is further explored in the green scenario by considering demand flexibility together with generation and storage options.

The remainder of the paper is organized as follows. Section 2 describes the methodological framework, including the optimization model, selected sites, load configuration, renewable resources, and input data. Section 3 presents the results obtained for the hybrid, renewable, and green scenarios, including system configurations, energy production, storage requirements, and economic performance. Section 4 discusses the main findings and compares them with previous studies. Section 5 summarizes the main conclusions, limitations, and perspectives for future research.

2. Materials and Methods

In this study, HOMER Pro was used to model and optimize the proposed off-grid hybrid microgrids [32]. The software allows for the simulation of different combinations of renewable generation, conventional generation, energy storage, and power conversion technologies and is widely applied to the techno-economic assessment of hybrid energy systems [9,12,14]. HOMER performs time-series energy balance calculations and evaluates feasible system configurations according to predefined technical and economic constraints, ranking the solutions based on their Net Present Cost (NPC).

The computational experiments were performed on a personal computer equipped with an Intel Core Ultra 7 155H processor (Intel Corporation, Santa Clara, CA, USA), operating at 3.8 GHz, 32 GB of RAM (5600 MHz), and the Microsoft Windows 11 operating system (Microsoft Corporation, Redmond, WA, USA). All simulations were performed using HOMER Pro 3.16 (HOMER Energy by UL, Boulder, CO, USA) [32].

2.1. Optimization Model

HOMER uses a proprietary derivative-free algorithm to search for the least-cost system. It ranks all feasible system configurations according to NPC. The NPC includes capital costs, replacement costs, operation and maintenance (O&M) costs, and fuel costs, and is calculated using Equation (1):

$$C_{NPC} = - \sum_{t=1}^T \frac{CF_t}{(1+i)^t} \quad (1)$$

where C_{NPC} is the NPC [\$], CF_t is the net cash flow [\$] in the year t , i is annual interest rate [%], and T is project lifetime [yr]. The objective function is to minimize the total NPC of Equation (2):

$$\text{Min} \sum_{n=1}^N C_{NPC}^n \quad (2)$$

where C_{NPC}^n denotes the NPC [\$] associated with component n .

The energy balance constraint is calculated for each time step of the year, and the operation of the generators and BESS is optimized. Operation of the system is simulated by making energy balance calculations for each of the 8760 h in a year [32]. Equation (3) represents the energy balance for the DC bus and Equation (4) for the AC bus.

$$\Delta t (P_{PV,t} + P_{WT,t} + P_{B,t}^{dg} + \eta_{AC} P_{AC,t}^{out} - P_{DC,t}^{out} - P_{B,t}^{cg} - P_{DC,t}^{Excess}) = 0 \quad \forall t \quad (3)$$

$$\Delta t (\eta_{DC} P_{DC,t}^{out} + P_{MH,t} + P_{DG,t} + P_{sg,t} - L_t - P_{AC,t}^{out} - P_{AC,t}^{Excess}) = 0 \quad \forall t \quad (4)$$

where $P_{PV,t}$ is the PV power output [kW] at hour t , $P_{WT,t}$ is the WT power output [kW] at hour t , $P_{MH,t}$ is the MH power output [kW] at hour t , $P_{DG,t}$ is the DG power output [kW] at hour t , $P_{B,t}^{dg}$ is the BESS discharge power [kW] at hour t , $P_{B,t}^{cg}$ is the BESS charge

power [kW] at hour t , $P_{AC,t}^{out}$ is the AC rectifier power input [kW] to the DC bus at hour t , $P_{DC,t}^{out}$ is the DC inverter power input [kW] to the AC bus at hour t , L_t is the AC load [kW] at hour t , $P_{DC,t}^{Excess}$ is the DC energy excess [kW] at hour t , $P_{AC,t}^{Excess}$ is the AC energy excess [kW] at hour t , and $P_{sg,t}$ is the capacity shortage [kW] at hour t ; η_{AC} and η_{DC} represent the efficiency of rectifier and inverter; and Δt is the length of the time step [h].

In the energy balance constraint, the capacity shortage represents the deficit of energy. HOMER performs all system types possible, and a system is considered feasible only if the deficit is less than the maximum annual capacity shortage. A cost penalty is applied to the system for any capacity shortage [32].

There are two dispatch strategies: (i) Load Following (LF); and (ii) Cycle Charging (CC). In the first one, it produces sufficient power to meet the load, and charging the storage bank or serving the deferrable load are lower-priority objectives and they are left to renewable sources. With this strategy, the controllable power sources (generators and storage banks) are dispatched at least in terms of total cost to supply the load and operation reserve. In the CC strategy, whenever a generator is on, it must operate at full output power, and the surplus goes toward serving the deferrable load and charging the storage bank. In this strategy, when a setpoint state of charge (SoC) is applied, HOMER avoids discharging the storage and a generator will be called upon to serve the load and to charge the storage bank until it reaches the setpoint SoC. The setpoint SoC reduces the number of battery charge–discharge cycles, reduces the number of generator starts, and avoids low SoC conditions [32].

The maximum battery charge ($P_{k,t,c}^{max,ksm}$) is calculated by Equation (5) using the kinetic storage model. Whether the storage can absorb all available surplus renewable power is calculated in each time step:

$$P_{k,t,c}^{max,ksm} = \frac{kQ_1 e^{-k\Delta t} + Qkc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \text{ [kW]} \quad (5)$$

where Q_1 is the available energy [kWh] in the storage at the beginning of the time step; Q is the total amount of energy [kWh] in the storage at the beginning of the time step; c is the storage capacity ratio [unitless]; and k is the storage rate constant [1/h]. The second constraint for battery charging is the maximum charge rate ($P_{k,t,c}^{max,rate}$), obtained from Equation (6):

$$P_{k,t,c}^{max,rate} = \frac{(1 - e^{-\alpha_c \Delta t})(Q_{max} - Q)}{\Delta t} \text{ [kW]} \quad (6)$$

where α_c is the maximum charge rate [A/Ah]; and Q_{max} is the capacity of the storage bank [kWh]. Finally, the third constraint on the charge power is the maximum charge current ($P_{k,t,c}^{max,current}$), which is obtained from Equation (7):

$$P_{k,t,c}^{max,current} = \frac{N_{bat} I_{max} U_{nom}}{1000} \text{ [kW]} \quad (7)$$

where N_{bat} is the number of batteries in the storage bank, I_{max} is the storage's maximum charge current [A], and U_{nom} is the storage's nominal voltage [V].

The maximum battery discharge power also must be calculated by the kinetic storage model. Maximum discharge power ($P_{k,t,d}^{max,ksm}$) varies based on charging and discharge history described in Equation (8):

$$P_{k,t,d}^{max,ksm} = \frac{-kcQ_{max} + kQ_1 e^{-k\Delta t} + Qkc(1 - e^{-k\Delta t})}{1 - e^{-k\Delta t} + c(k\Delta t - 1 + e^{-k\Delta t})} \text{ [kW]} \quad (8)$$

Assuming the discharging losses, Equation (9) presents the maximum discharge power ($P_{k,t,d}^{max}$):

$$P_{k,t,d}^{max} = \eta_{B,d} P_{k,t,d}^{max,ksm} \quad [\text{kW}] \quad (9)$$

where $\eta_{B,d}$ represents the BESS discharge efficiency.

The battery lifetime (R_{bat}) can be limited by two factors: (i) the lifetime throughput, resulting from Equation (10); and (ii) the storage float life. Thus, the storage lifetime can be limited by time, throughput, or both:

$$R_{bat} = \frac{N_{bat} Q_{lifetime}}{Q_{th}} \quad [\text{yr}] \quad (10)$$

where $Q_{lifetime}$ is the lifetime throughput of a single storage [kWh]; and Q_{th} is the annual storage throughput [kWh/yr]. In the lifetime throughput strategy, the storage will require replacement after a fixed number of charge–discharge cycles. The lifetime storage throughput is used to calculate the life of the storage bank and the storage wear cost.

To summarize, the decision variables are the size of the PV array; the number and type of WT; the number of MH; the size of DG; the number of batteries; the size of the converter; and the dispatch strategy. The complete formulation can be found in the user manual [32].

2.2. Study Locations and Regional Context

The Legal Amazon covers approximately 5.2 million km², corresponding to about 61% of the Brazilian territory, and encompasses all or part of nine Brazilian states. Three study locations were selected in Amazonas (AM), Roraima (RR), and Tocantins (TO), as shown in Figure 2.

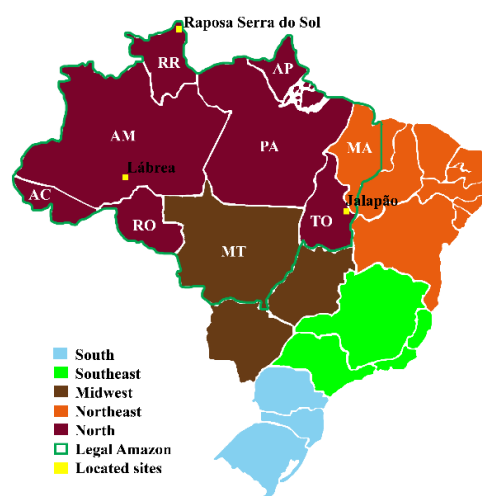


Figure 2. Geographical location of the three study areas within the Legal Amazon [31].

Lábrea is a region of an extractive reserve (RESEX). RESEX are protected territorial spaces whose objective is the protection of livelihoods and the culture of traditional populations, as well as ensuring the sustainable use of natural resources. The Lábrea region (-7.23° , -64.82°) was chosen for Amazonas, close to the Purus River and 700 km from Manaus (Capital of Amazonas). An indigenous territory in Raposa Serra do Sol (RSS) (4.45° , -60.10°) was chosen for Roraima; in recent years, there have been attempts to electrify this region. Finally, a quilombola community (a community formed by former African slaves and Afro-descended people) in Jalapão (-10.14° , -46.50°) was chosen for Tocantins. The selection of these communities is consistent with the population profile addressed by federal electrification initiatives for remote areas of the Legal Amazon, including the MLA [19].

2.3. Load Configuration

According to the normative resolution 1000/2021 of Brazil, the electricity supply in isolated areas may be provided through a microsystem for electrical power generation and distribution (Microssistema Isolado de Geração e Distribuição de Energia Elétrica, MIGDI) [33]. The MIGDI is an isolated microgrid with a total installed generation power of up to 100 kW; Consumer Units (CU) must have a monthly guarantee of at least 45 kWh/CU and minimum autonomy of 36 h for PV and 48 h for other resources. Most of the time, these microgrids typically serve loads between 5 and 50 kW [34]. It is important to consider that with electrification, there is usually the emergence of previously suppressed demand and an increase in population due to local development [23]. Thus, an energy demand of 80 kWh/CU per month [35] and a community with 50 CU will be considered. A synthetic hourly profile generated by HOMER Pro was adopted, as estimating demand in un-electrified areas is an inherent challenge in greenfield projects. The community daily load profile from HOMER base data was used, with a load factor of 22% and peak load at 18:00; it is similar to government guidelines for rural electrification [34].

2.4. Renewable Resources

Brazil has great potential for PV energy; the regions with the lowest averages are in the south (3.5 kWh/m².day). The local solar irradiation data were obtained from the Sun-Data database maintained by the Reference Center for Solar and Wind Energy (Centro de Referência para Energia Solar e Eólica, CRESESB) [36]. For Lábrea, RSS, and Jalapão, the annual daily solar radiation averages are 4.46, 5.20, and 5.57 kWh/m²/day, respectively. Wind speed has different behavior throughout Brazilian territory. Although the wind potential in this region of the Amazon forest is relatively low, there is a technically exploitable potential in the north of Roraima and the coastal areas of Pará and Amapá [30]. The local wind speed data were obtained from the NASA database available through HOMER [32]. For Lábrea (altitude: 60 m), RSS (altitude: 500 m), and Jalapão (altitude: 500 m), the annual wind speed averages are 1.64, 6.23, and 4.46 m/s, respectively. In view of the great potential that exists in the region, MH and mini-hydro generation may provide a suitable option for serving these communities [34]. Data were obtained from the National Water Agency (Agência Nacional de Água e Saneamento Básico, ANA) database [37]. For Lábrea, the annual water speed average is 1.06 m/s, and for RSS and Jalapão, the annual streamflow averages are 214 m³/s and 59.2 m³/s, respectively.

Although annual averages are reported for comparison, all HOMER Pro simulations were performed at an hourly resolution (8760 h/year). Evaluating the system on a full-year hourly basis is essential, as simplified temporal representations (such as typical days or monthly averages) fail to capture critical generation–demand mismatches, ramping requirements, and storage dynamics in systems with variable renewable generation [38]. Hourly solar irradiance profiles were synthesized by HOMER from historical monthly CRESESB/CEPEL averages combined with NASA clearness indices, while hourly wind speed series were generated directly from HOMER's integrated NASA POWER long-term database. For the micro-hydro (MH) systems in RSS and Jalapão, because the 5 kW modular Pelton design requires a minimal discharge (25 L/s at a fixed 15 m head) well within the perennial rivers' dry-season baseflow (ANA records), seasonal streamflow variations do not constrain operation.

Due to technical, economic, and environmental barriers in remote areas, biomass was not considered in this work. Similarly, biodiesel was not considered due to the difficulty of production and importation to remote areas. Vegetable oils were not considered because they are valuable products for the cosmetic industries, and biogas was not considered because of the lack of experience with successful cases and because it is not a modular technology [33]. Moreover, biomass use may promote deforestation [23].

2.5. Input Data

The schematic diagram of the DG–WT–PV–MH–BESS microgrid system proposed is presented in Figure 3. Table 1 presents the nominal specifications and cost parameters of each component.

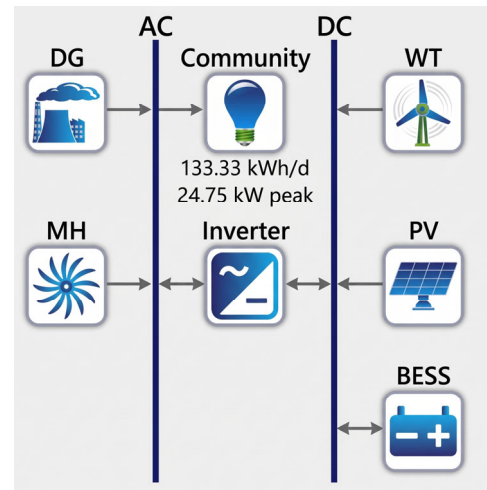


Figure 3. Schematic architecture of the evaluated DG–WT–PV–MH–BESS microgrid (unidirectional arrows indicate generation/demand power flow, while bidirectional arrows indicate bidirectional power conversion and storage charging/discharging).

Table 1. Technical and economic parameters adopted for microgrid components.

	Description	Specification
1. General	Load (kWh/yr)	48,637
	Project Lifetime (years)	25
	Discount Rate: [39]	6%
	Inflation Rate: [39]	3.5%
2. Diesel Generator	Fuel in AM, RR and TO (US\$/l) [40]	1.68; 1.56; 1.55
	CAPEX (US\$/kW) [41]	200.00
	O&M (US\$/hr) [41]	0.05
	Lifetime (hours)	15,000
3. Wind Turbine	CAPEX (US\$/kW) [42,43]	983.33 (Zeus) 950.00 (Verne)
	O&M (US\$/kW/yr) [41]	50.00
	Lifetime (years)	20
	Hub Height (m)	15
4. Photovoltaic	CAPEX (US\$/kWp) [44]	763.00
	O&M (US\$/kWp/yr) [44]	7.63
	Lifetime (years)	25
	Module Efficiency (%)	20.38
5. Micro-Hydro	CAPEX (US\$/kW) [45,46]	4000.00
	O&M (US\$/kW/yr) [41]	100.00
	Lifetime (years)	15
6. Battery System	Capacity (kWh-kW)	1-1
	CAPEX (US\$/kWh) [39]	765.00
	O&M (US\$/ kWh/yr) [39]	7.65
	Lifetime (years)	15
7. Inverter	CAPEX (US\$/kW) [44]	115.00
	O&M (US\$/kW/yr) [44]	1.15

Lifetime (years)	10
Efficiency (%)	95

The 15-year BESS lifetime is defined considering one cycle per day; this value is used to calculate the lifetime throughput ($Q_{lifetime}$). For DG, a generic generation with power capacity of 5 kW was assumed. Two types of WT were used: the first one is Zeus (TESUP Global Ltd., London, UK), of 3.1 kW and with a diameter of 2.25 m [43]; the second turbine is a national model, Verne 555 (Enersud Soluções em Energia, Maricá, Brazil), of 6 kW and with a diameter of 5.55 m [42]. PV modules of 410 Wp (JinkoSolar Holding Co., Ltd., Shanghai, China) and with a Fronius inverter model (Fronius International GmbH, Pettenbach, Austria) were used. Due to the low slope and the environment impacts caused by dams, the small hydrokinetic turbine (SHT) SMART Monofloat (Smart Hydro Power GmbH, Tutzing, Germany), with a rotor of 1 m and a maximum power output of 5 kW at 2.8 m/s, was chosen. This type of hydropower has already been implemented in Colombia (which borders with Brazil) to replace a few DG on rice farms, with a water velocity of 1.7 m/s [45]. RSS and Jalapão include sites with waterfalls suitable for MH generation. Therefore, a modular 1 kW Pelton MH turbine developed by Hidreo (Hidreo Energy Solutions, Curitiba, Brazil) was selected, requiring a minimum flow of 5 L/s and a hydraulic head of 15 m made by Hidreo [46]. The number of MH was limited to five (5 kW) to reduce the environmental impact.

3. Results

In this study, the analysis considers three Amazonian locations with contrasting social and environmental conditions to assess alternative techno-economic configurations for rural electrification. HOMER Pro version 3.16 is used to assess each microgrid system using the search space and sorting them in terms of the total NPC [32]. The search space variables directly impact the simulation time since HOMER performs Equations (3) and (4) for all possible combinations. Therefore, the search space was limited, such as, the DG size (0, 5, 10, ..., 25, 30 kW), the number of WT (0, 1, 2, 3, ..., 10), and the number of SHT/MH (0, 1, 2, 3, 4, 5), using sensitivity analysis tools. The maximum limits for the PV array size, the number of batteries, and the converter size have not been defined. The community consists of 50 CU, with a peak load of 24.75 kW and an annual load of 48,637 kWh.

3.1. Hybrid Microgrid Configurations with DG

Table 2 presents the three highest-ranked configurations optimized for each location in the scenario where DG is considered. For WT, the first number in the column is for the Zeus turbine (3.1 kW) and the second one is for the Verne turbine (6 kW).

Table 2. Highest-ranked hybrid microgrid configurations for each study location.

Location	DG (kW)	WT (kW)	PV (kWp)	SHT/MH (kW)	BESS (kWh)	Inverter (kW)	NPC (USD)	COE (USD/kWh)	Fuel (L)	Excess Production (%)
Lábrea-1	15	0	72.6	0	123.6	20.4	271,310	0.300	1225	43.0
Lábrea-2	10	3.1+0	87.9	0	121.5	18.9	272,741	0.302	771	52.5
Lábrea-3	15	0+6	72.9	0	123.6	20.5	283,435	0.313	1213	43.2
RSS-1	5	6.2+0	7.8	5	40.8	14.6	119,699	0.132	118	18.4
RSS-2	5	0+6	10.5	5	39.8	14.2	121,397	0.134	127	24.2
RSS-3	5	3.1+6	8.6	5	36.8	13.8	122,205	0.135	152	28.0
Jalapão-1	5	6.2+0	11.7	5	40.8	12.5	123,531	0.137	147	21.1
Jalapão-2	10	0	12.3	5	48.0	13.4	125,510	0.139	269	13.1
Jalapão-3	5	0+6	15.4	5	41.9	15.2	127,665	0.141	116	26.6

For Lábrea, the optimization selected a DG–PV–BESS configuration. Local wind conditions are unfavorable for WT deployment, with an annual mean wind speed of only 1.64 m/s at 10 m. Likewise, the combination of hydrokinetic generation cost and the low water velocity of the Purus River (1.06 m/s) limits the economic attractiveness of this resource at the site. Although the selected configuration includes 15 kW of DG capacity, DG supplies only 6.8% of the annual energy demand. In contrast, the BESS delivers 25,185 kWh/yr, corresponding to 51.8% of the annual load, and therefore plays a substantial role in supporting PV integration and limiting diesel consumption. This contribution comes with a considerable economic impact, as the BESS represents 60.4% of capital costs, 92.8% of replacement costs, and 59.6% of O&M costs, as shown in Figure 4.

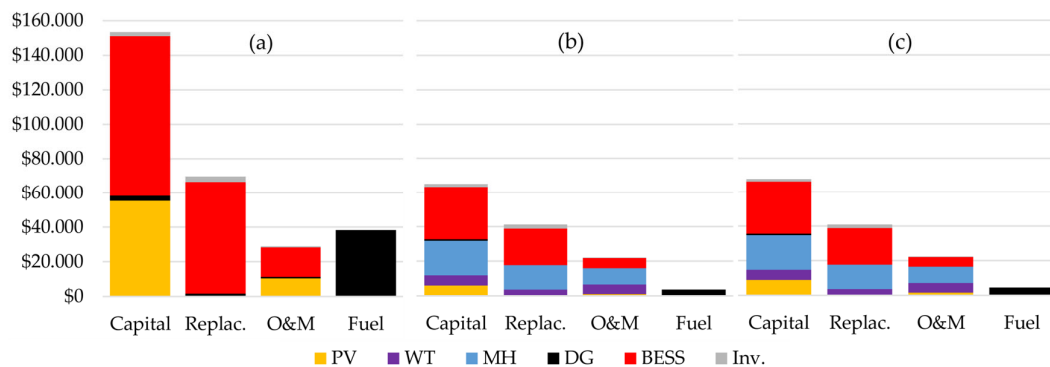


Figure 4. Breakdown of NPC by cost category and system component for (a) Lábrea, (b) RSS, and (c) Jalapão.

For RSS and Jalapão, the availability of small waterfalls favored the inclusion of MH in the optimized configurations. An intra-site comparison for Jalapão reveals that MH independently reduces diesel consumption by 79.9% (from 730 to 147 L/yr), required BESS capacity by 53.5% (from 87.8 to 40.8 kWh), and the total NPC by 27.4% compared to an optimized non-hydro configuration. Owing to year-round water availability, the 5 kW MH system operated continuously at full design flow (8760 h/yr), delivering a constant 4.38 kW baseload after accounting for turbine efficiency and hydraulic losses (an 87.6% effective capacity factor). Consequently, DG operation was limited to 143 h/yr in RSS and 166 h/yr in Jalapão, supplying only 0.7% and 0.9% of the respective annual loads. Sensitivity analysis further showed that restricting MH capacity to four units shifted the optimized configuration toward three WT units. RSS presented the most favorable wind resource among the evaluated sites, with an annual mean wind speed of 6.23 m/s, where two Zeus WT generated 12,047 kWh/yr (25% of the annual load). Under the same WT arrangement in Jalapão (4.46 m/s), energy production was approximately half that obtained in RSS.

Figure 5 shows the daily dispatch on the day with the highest annual daily energy consumption (August 10, totaling 170.14 kWh). Figure 5a illustrates the typical PV-dominated daily dispatch of the Lábrea microgrid. Overnight demand is supplied exclusively by the BESS, with the SoC decreasing from an initial 55.2% at midnight to a minimum of 33.7% at 07:00, while the DG remains offline. As solar irradiance rises, the BESS begins charging at 08:00 and achieves full capacity (100% SoC, 123.6 kWh) by 12:00 under the LF dispatch strategy. Consequently, between 12:00 and 16:00, substantial PV curtailment occurs, coinciding with a peak PV generation of 50.63 kW at 13:00. The daily energy surplus reaches 122.27 kWh, which accounts for 42.5% of the total PV energy available (287.5 kWh) and 71.9% of the total daily energy demand. During the evening peak demand at 18:00 (22.01 kW), the DG is dispatched at 3.75 kW to complement the 19.22 kW supplied by

BESS discharge. Annually, overproduction of PV corresponds to 40,170 kWh in Lábrea. The high level of excess energy results from PV overcapacity, which is economically favored by the lower cost of PV modules compared with the high cost of BESS capacity.

Figure 5b,c illustrate the daily operational dispatch for RSS and Jalapão, where MH delivers a continuous 4.38 kW baseload throughout the 24 h cycle. In both systems, this firm baseload reduces the required BESS capacity to 40.8 kWh, an approximate 67% reduction compared to the 123.6 kWh required in Lábrea. To ensure the 22.01 kW evening peak at 18:00, the BESS discharges 14.91 kW, driving the SoC to a minimum of 17.54% (7.09 kWh) at 20:00–21:00 before overnight hydro and wind generation recharge the bank to 100% by 03:00. Conversely, in Jalapão (Figure 5c), the BESS discharge is capped at 11.88 kW during the 18:00 peak due to inverter sizing, requiring the DG to operate in peak-shaving mode (5.00 kW at 18:00, with auxiliary support of 1.25 kW and 2.38 kW at 20:00 and 21:00, respectively) to prevent unserved demand while bounding the BESS at the same 17.54% minimum SoC. Coincident daytime solar production (peaking at 5.32 kW in RSS and 8.61 kW in Jalapão) causes substantial diurnal energy curtailment once BESS reaches full charge.

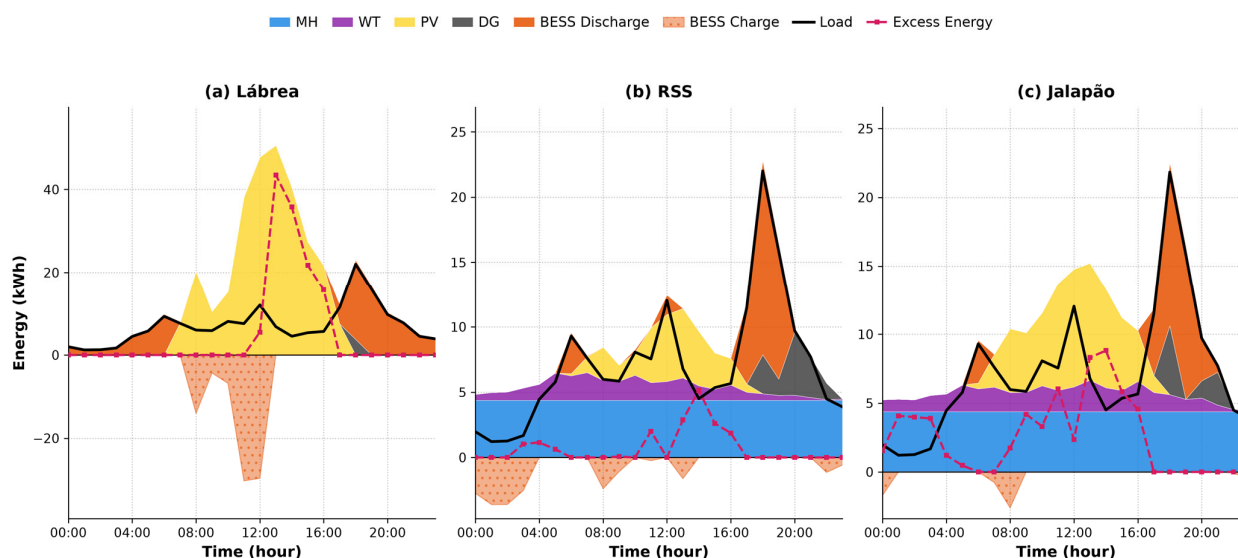


Figure 5. Daily operational dispatch profiles on the day of maximum annual energy consumption (10 August) for the (a) Lábrea, (b) RSS, and (c) Jalapão microgrids.

Throughout the year, the DG reached its 15 kW rated capacity on only eleven days in Lábrea, with the highest daily diesel production occurring on 12 January (in the summer rainy season). Figure 6 illustrates this critical dispatch scenario, in which heavy cloud cover suppresses PV generation (peaking at only 12.29 kW) and eliminates any energy surplus. Under this severe solar deficit, the DG supplies 40.2% of the daily energy requirement. Because the BESS recovers to only 30.95% SoC (38.33 kWh) before depleting to its 17.54% operational minimum at 17:00, the DG operates for 12 h, maintaining base support at its 3.75 kW technical minimum and ramping up to its 15.0 kW ceiling during the 19:00 peak load (15.97 kW).

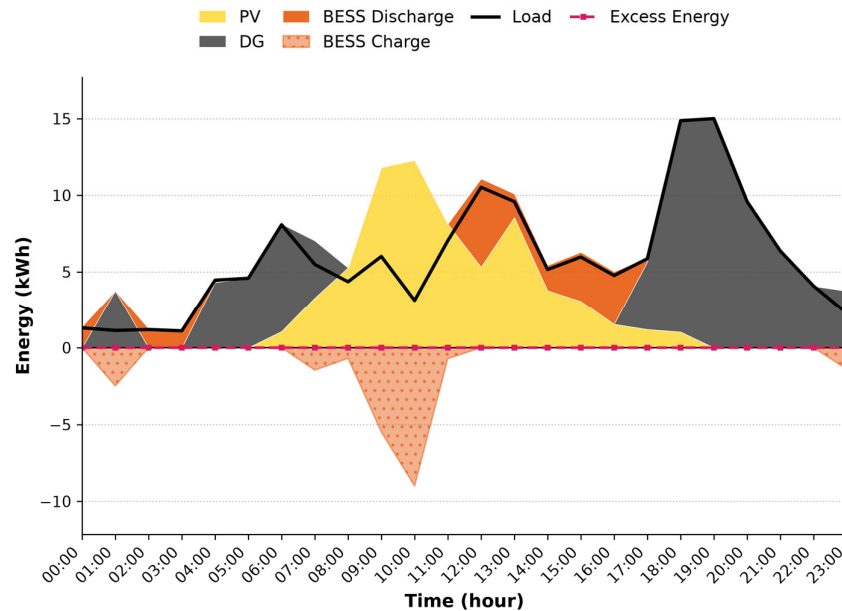


Figure 6. Daily operational dispatch of the Lábrea microgrid on the day of maximum annual DG (12 January).

Figure 7 presents the operational dispatch for RSS on the annual peak wind day (9 February), compared with the peak PV day shown in Figure 5b (10 August). Sustained WT at its 5.65 kW rated capacity alongside the constant 4.38 kW hydro baseload keeps the DG deactivated and produces an energy surplus of over 50%. Comparing both figures demonstrates seasonal resource complementarity: relatively low wind conditions during the higher-PV period are offset by stronger wind production during the overcast February period. These complementary dynamics limit BESS utilization strictly to minor evening support, preserving the SoC above 71.9% and reducing BESS cycling requirements compared with a less diversified generation profile.

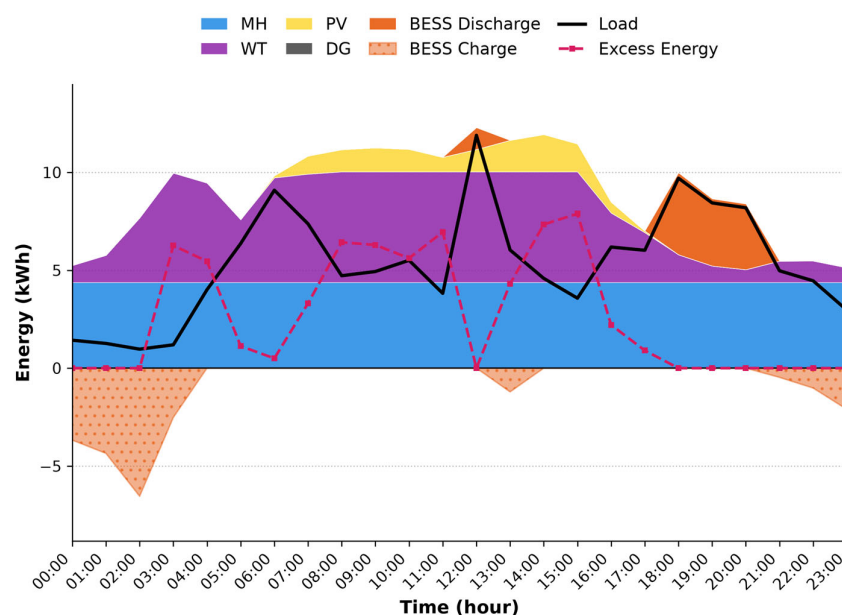


Figure 7. Daily operational dispatch of the RSS microgrid on the annual peak wind generation day (9 February).

3.2. Fully Renewable Microgrid Configurations

In the fully renewable scenario, DG is excluded and the load is supplied exclusively by renewable generation and BESS. Table 3 presents the three highest-ranked solutions for each location. In Lábrea, the selected configuration includes three Zeus WT, which together generate 2555 kWh/yr, corresponding to 5.25% of the annual energy consumption. The resulting WT capacity factors are 3.14% in Amazonas, 22.9% in Roraima, and 13.3% in Tocantins.

Table 3. Highest-ranked fully renewable microgrid configurations for each study location.

Location	WT (kW)	PV (kWp)	SHT/MH (kW)	BESS (kWh)	Inverter (kW)	NPC (USD)	COE (USD/kWh)	Excess Production (%)
Lábrea-1	9.3 + 0	184.7	0	123.6	27.1	350,953	0.388	77.0
Lábrea-2	0	175.9	0	141.9	56.9	355,313	0.393	75.5
Lábrea-3	9.3 + 6	184.7	0	123.6	27.1	363,417	0.402	77.0
RSS-1	3.1 + 0	19.1	5	50.0	20.1	132,396	0.146	29.4
RSS-2	0 + 6	16.5	5	50.0	20.7	136,330	0.151	32.6
RSS-3	0	25.6	5	55.1	20.0	138,364	0.153	32.3
Jalapão-1	9.3 + 0	16.5	5	44.9	21.0	136,434	0.151	32.4
Jalapão-2	0	31.5	5	51.1	20.4	138,673	0.153	42.2
Jalapão-3	0 + 6	20.8	5	51.1	21.3	141,661	0.157	34.4

The WT generation compensated for the removal of the DG gap in Lábrea and Jalapão, although the installed capacity was reduced in RSS as a consequence of the inverter price impact.

The inverter sizing is governed by the peak residual AC demand that must be transferred from the DC-coupled assets (Equations (3) and (4)). In Lábrea, where no AC-side hydro generation is available ($P_{MH} = 0$), the converter must supply the entire 24.75 kW peak load, resulting in a 27.1 kW inverter capacity. In contrast, for RSS and Jalapão, the continuous 4.38 kW micro-hydro generation on the AC bus directly relieves the inverter, reducing net peak DC-to-AC transfer to approximately 20.37 kW. The slight difference between Jalapão (21.0 kW) and RSS (20.1 kW) stems from the DC-bus generation mix: to compensate for lower wind speeds, Jalapão incorporates 9.3 kW of WT capacity (versus 3.1 kW in RSS). In RSS, an inverter capacity of 20.1 kW was techno-economically selected, as the marginal capacity deficit during extreme peak hours results in an insignificant annual unmet load of only 0.099%. If the WT is changed to an AC bus, the number of WTs increases to three.

The monthly electric production for this solution is presented in Figure 8. Limited seasonal variation in PV production and higher wind production are observed in the summer (November–March), when more production is required for cooling. Although the Verne WT does not appear as the first solution in Tables 2 and 3, it always appears among the most feasible solutions.

Despite the much lower WT participation in the Amazonas state, it reduces the BESS requirement by 12.7% and the NPC by 1.2% compared to the second solution. Figure 9 illustrates how the WT reduces the BESS requirement during peak hours in Lábrea, the location with the lowest wind speed in this study. The CC dispatch strategy was chosen.

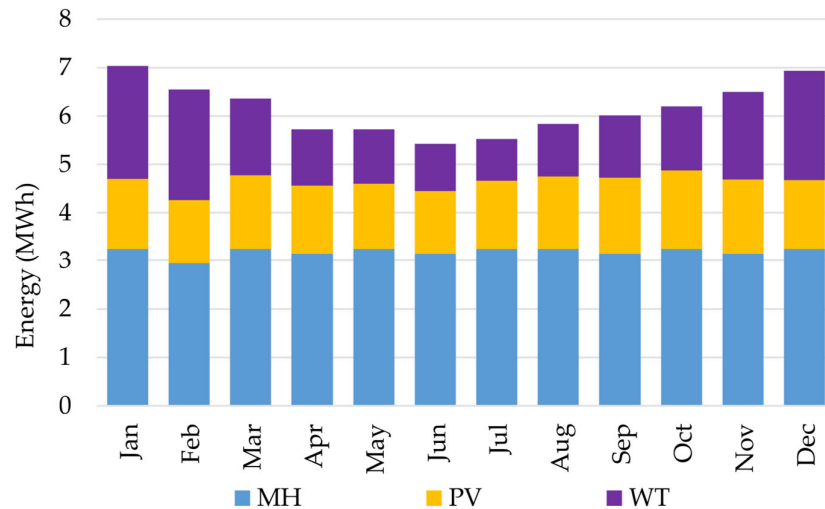


Figure 8. Monthly energy production in RSS.

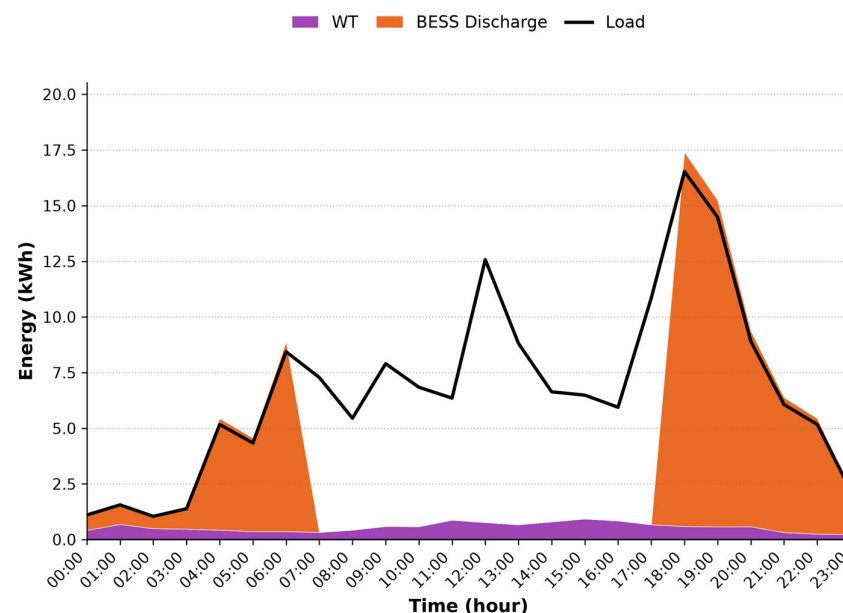


Figure 9. Day with maximum WT production in Lábrea.

3.3. Green Scenario

For the green scenario, the assumed lifetime of WT and SHT/MH was set to 25 years. BESS and SHT/MH costs were reduced by 15%, while the water velocity considered for Amazonas increased by 15% and the WT hub height was raised to 30 m. In addition, a maximum annual capacity shortage of 5% was allowed. This parameter represents the fraction of demand that may remain unmet during the simulation and was introduced to assess the effect of greater demand-side flexibility on system sizing. In practice, part of this flexibility could be provided through DR strategies involving controllable loads.

The combined effect of the lower BESS cost and the 5% capacity-shortage allowance reduced both storage and peak-capacity requirements, as shown in Table 4. In Lábrea, WT was no longer included in the optimized configuration, while PV capacity decreased by 58.3%. Although the assumed BESS cost was reduced by only 15%, NPC decreased by 53.5%. Allowing a limited fraction of unmet demand reduces the need to oversize components that would otherwise operate mainly during short peak-demand periods.

Nevertheless, excess energy production in Lábrea remained at 46.9%, indicating that DR could potentially shift flexible demand toward periods of surplus generation and thereby reduce both excess energy and unmet demand.

Table 4. Optimized microgrid configurations obtained under the green scenario for each study location.

Location	WT (kW)	PV (kWp)	SHT/MH (kW)	BESS (kWh)	Inverter (kW)	NPC (USD)	COE (USD/kWh)	Excess Production (%)
Lábrea	0	77.1	0	119	28.1	163,038	0.190	46.9
RSS	6.2 + 0	4.3	5	29.6	6.3	76,126	0.089	18.4
Jalapão	6.2 + 0	6.5	5	30.6	6.3	79,133	0.092	15.7

Raising the WT hub height increased wind energy production by 6.6%. The optimized configurations for both Roraima and Tocantins included two Zeus WT; however, differences in the local wind regimes resulted in 71.9% higher energy production in Roraima. Although the Zeus model has a slightly higher installed cost per kWh than the Verne WT, optimization favored the Zeus model due to its power curve.

To isolate the individual drivers of the green scenario in Lábrea, sensitivity runs were conducted. Permitting a 5% capacity shortage independently reduces the LCOE from 0.388 to 0.204 USD/kWh by eliminating the severe PV and BESS oversizing otherwise required for rare peak hours. Conversely, increasing local water velocity by 15% alone fails to justify the economic viability of hydrokinetic (SHT) deployment in the Purus River, resulting in an increased LCOE of 0.343 USD/kWh due to over-allocation.

4. Discussion

Comparative assessment across the three locations shows how differences in wind, solar, and hydropower availability influence the techno-economic configuration of hybrid microgrids for rural electrification in the Amazon region. In addition, where hydropower resources are unavailable, a DG–PV–BESS system provides the lowest-cost configuration among the alternatives evaluated. In this scenario, the PV–BESS system reduced diesel consumption, with DG accounting for only 6.8% of the annual electricity production in the least favorable case. Previous studies have also identified DG–PV–BESS systems as suitable alternatives for the Amazon region, although with a diesel contribution of 14.4% [29]. Similar hybrid systems are already operating in parts of the region [26].

Where suitable hydropower and wind resources were available, the DG–WT–PV–MH–BESS microgrid presented the lowest cost, with a COE of approximately 0.13 USD/kWh (RSS) and 0.14 USD/kWh (Jalapão). Despite the moderate wind resources at some locations, wind generation contributed during nighttime and peak-demand periods, reducing storage requirements and system costs. This configuration also reduced BESS capacity and diesel consumption, as shown in Figure 4. Few studies have reported the combined use of diesel, wind, PV, micro-hydro, and BESS in the Amazon region. The experimental projects reported in the literature have mainly evaluated WT–DG, WT–PV–DG, and WT–PV systems in coastal areas [18,26].

The renewable energy scenario resulted in a COE of approximately 0.15 USD/kWh (RSS and Jalapão) and 0.39 USD/kWh (Lábrea). The simulations also indicated complementarity among wind, hydropower, and solar generation. In this scenario, WT compensated for the removal of DG, differing from the configuration reported by Costa and Vilalva [29]. Wind generation may therefore contribute to fully renewable systems even in locations with moderate wind resources. Achieving 100% renewable electricity supply increased system costs by 29.4% in Amazonas and by 10.5% in Roraima and Tocantins.

Across the evaluated cases, wind generation contributed to reductions in storage requirements and NPC, including in locations with low average wind speeds, as shown by the Lábrea-2°, RSS-3°, and Jalapão-2° configurations in Table 3.

Regarding regulatory compliance with ANEEL Resolution 1000/2021 (100 kW ceiling for MIGDI), the critical scenario occurs in fully renewable Lábrea, where the DC capacity reaches 194.3 kWp. Because generation and storage are DC-coupled, AC grid injection is physically bounded by the 27.1 kW inverter (or 35.4 kW with the backup DG in the hybrid case), operating well below the 100 kW threshold, with surplus peak generation intentionally curtailed. Similarly, while prescriptive standards suggest 36–48 h of static autonomy (267 kWh), Lábrea's renewable configuration operates with only 105 kWh of BESS (21 h). The 8760 h dynamic simulation confirmed zero unserved energy, as the oversized PV array captures sufficient diffuse radiation, even on overcast days, to sustain the load and replenish the batteries. In RSS and Jalapão, the continuous 4.38 kW hydro baseload naturally ensures multi-day security, making large static battery banks economically redundant.

In the green scenario, the available hydrokinetic resource in Amazonas was insufficient to support the inclusion of a SHT in the selected configuration. Few hydrokinetic projects have been reported in the Amazon region. Examples include an experimental 500 W SHT project [26] and a 1 kW SHT installed on the Maracá River, in the state of Amapá, with support from the Light for All program [26]. Allowing a limited capacity shortage as a proxy for demand-side flexibility reduced the COE, installed capacity, excess energy production, and BESS requirements. In isolated communities, such flexibility could be provided through DR strategies involving controllable loads, including water pumps, refrigerators, fans, air-conditioning units, and public lighting. Under the adopted sensitivity conditions, including lower BESS and hydropower technology costs, the model identified a microgrid configuration with a COE of approximately 0.09 USD/kWh (RSS and Jalapão) and 0.19 USD/kWh (Lábrea). These results indicate the potential of DR to improve the techno-economic performance of renewable microgrids when flexible loads can be shifted to periods of surplus generation. Such configurations are also consistent with the broader objectives of the MLA, which associates electricity access in remote Amazonian communities with social and economic development and the sustainable use of local resources [19].

As summarized in Table 5, cross-scenario comparisons demonstrate that achieving 100% renewable supply imposes only a moderate cost premium at multi-resource sites (+10.5% NPC in RSS and Jalapão), whereas the single-resource site of Lábrea incurs a 29.4% penalty due to severe PV/BESS oversizing to cover peak demand. In the green scenario, mature-technology cost reductions and demand-side flexibility reduce levelized costs to 0.089–0.092 USD/kWh in hydro-endowed communities and 0.190 USD/kWh in Lábrea. Furthermore, wind power plays a strongly heterogeneous role governed by local geography: in wind-abundant RSS (6.23 m/s), two 3.1 kW WT units supply 25% of the annual demand (12,047 kWh/yr), complementing the solar dip during overcast months. In moderate-wind Jalapão (4.46 m/s), the same turbine arrangement generates approximately half that amount, requiring up to three WT units (9.3 kW) in the fully renewable case to displace residual diesel. Conversely, in Lábrea, the calm equatorial regime completely excludes wind integration across all scenarios, shifting the entire storage burden to the BESS.

Table 5. Consolidated techno-economic performance across the evaluated sites and scenarios.

Location	Scenario	NPC (USD)	COE (USD/kWh)	Ren. (%)	BESS (kWh)	Fuel (L/yr)	Excess Production (%)
Lábrea	Hybrid	271,310	0.300	93.2	123.6	1225	43.0
	100% Ren.	350,953	0.388	100	124.0	-	77.0
	Green	163,038	0.190	100	119	-	46.9
RSS	Hybrid	119,699	0.132	99.3	40.8	118	18.4
	100% Ren.	132,396	0.146	100	50.0	-	29.4
	Green	76,126	0.089	100	29.6	-	18.4
Jalapão	Hybrid	123,531	0.137	99.1	40.8	147	21.1
	100% Ren.	136,434	0.151	100	44.9	-	32.4
	Green	79,133	0.092	100	30.6	-	15.7

Allowing for a limited capacity shortage served as a proxy for sizing to evaluate demand-side flexibility. While HOMER treats this as unserved energy (resulting in an annual unmet load of 5.08%), our energy balance proves that excess generation is readily available. In practice, implementing Demand Response (DR) via controllable loads, such as water pumps, refrigeration, and rural machinery, would shift this energy rather than shedding it, capturing the economic benefits of reduced component sizing without compromising supply continuity.

In 2025, the COE for supplying the Lábrea region was 0.340 USD/kWh, while in Roraima it was 0.231 USD/kWh. The highest reported value was 13.353 USD/kWh in Pará for a biomass-based system [47]. For context, the current subsidized electricity tariffs are 0.132 USD/kWh in Amazonas, 0.110 USD/kWh in Roraima, and 0.123 USD/kWh in Tocantins. The COE obtained in the present study was also lower than that reported for a PV–WT–MH–BESS system proposed for Amazonian communities in Ecuador [48]. In addition, ref. [27] evaluated a system composed of a fuel cell, electrolyzer, PV, DG, and BESS, for which the lowest reported COE was 1.072 USD/kWh. These comparisons indicate that the configurations proposed in the present study have COE values within or below the range reported for other hybrid systems designed for isolated Amazonian communities.

A limitation of this study is the assumption of a static baseline load. In practice, newly electrified communities experience a rebound effect: residential demand expands as households acquire additional appliances, while local productive activities (e.g., agro-processing, ice production for fishing, and water pumping) become electrified.

5. Conclusions

This study evaluated hybrid microgrid configurations for rural electrification across three locations in the Brazilian Legal Amazon with varying solar, wind, and hydropower resources. The results indicate that system configuration depends on the availability and complementarity of local energy resources. Where continuous hydropower resources were available, micro-hydro generation reduced BESS requirements and diesel consumption, while wind generation complemented PV production during nighttime and periods of low solar irradiance. In locations with limited hydro and wind resources, PV generation combined with BESS remained feasible, although it resulted in higher costs and excess electricity production. In the green scenario, the COE reached 0.089 USD/kWh in Roraima and 0.092 USD/kWh in Tocantins, indicating that demand-side flexibility and reductions in technology costs can affect the economic performance of renewable microgrids. Local technical assessments remain necessary to obtain representative data on renewable resources and demand and to evaluate the social and environmental conditions associated with each project.

The configurations obtained in this study should be considered techno-economic reference cases rather than final project designs. Resource uncertainty, load growth, distribution-network constraints, and site-specific social and environmental conditions were not fully represented. In addition, the HOMER software does not explicitly account for multi-objective optimization or uncertainty. Future work will extend this framework to agricultural microgrids, including center-pivot irrigation systems, by incorporating load forecasting and energy-management strategies suitable for deployment on edge hardware. These approaches will be evaluated for the coordinated management of renewable generation, storage systems, and irrigation loads, considering the operating costs, fossil-fuel consumption, and the energy requirements of agricultural production.

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Abbreviations

The following abbreviations are used in this manuscript:

IEA	International Energy Agency
SGD 7	Sustainable Development Goal 7
HRES	Hybrid Renewable Energy Systems
DG	Diesel Generators
COE	Cost of Energy
PV	Photovoltaic
BESS	Battery Energy Storage Systems

MH	Micro-Hydro
WT	Wind Turbine
ONS	National Electric System Operator
MLA	More Light for the Amazon
SISOL	Brazilian Isolated Systems
EPE	Energy Research Office
BD	Benders Decomposition
RH	Rolling Horizon
DR	Demand Response
NPC	Net Present Cost
O&M	Operation and Maintenance
CC	Cycle Charging
AM	Amazonas
RR	Roraima
TO	Tocantins
RSS	Raposa Serra do Sol
MIGDI	Isolated Microsystem for Electrical Power Generation and Distribution
CU	Consumer Units
CRESESB	Reference Center for Solar and Wind Energy
ANA	National Water Agency
SHT	Small Hydrokinetic Turbine
SoC	State of Charge
LF	Load Following

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