THE BARRIERS TO 100% RENEWABLE ISOLATED MINIGRIDS: WHY DO COMBUSTION GENERATORS STILL DOMINATE?

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Summary

Isolated minigrids in the Brazilian Amazon, which currently rely heavily on diesel generation, face significant challenges related to fuel logistics, environmental impact, and cost volatility. This study explores the potential of hybrid renewable energy systems (HRES), combining photovoltaic generation (PV), battery storage (BESS), and diesel gensets, to support the region's energy transition. Using real load and meteorological data from three contrasting communities (Fernando de Noronha, Tefé, and Iauretê), we simulate various renewable fraction (RF) scenarios, from 90% to 100%, using HOMER Pro®. Results reveal that while achieving a 90% RF is technically feasible with moderate increases in photovoltaic and battery storage capacity, the push toward 100% RF requires exponentially greater infrastructure, averaging an 83% increase in PV and a 237% increase in storage. This "last-mile" effect is consistent across all sites regardless of community size or solar resource, highlighting BESS as the primary technical and economic constraint. Additionally, per capita energy infrastructure requirements escalate sharply at higher RF targets, posing challenges for scalability and environmental licensing. The findings suggest that while minigrids with high shares of renewables are a promising solution for decarbonization and improving energy access, full autonomy from diesel remains economically prohibitive under current conditions. A phased energy transition strategy aiming for 80–90% RF, combined with complementary technologies such as biofuels or long-duration storage, is recommended. These insights can guide infrastructure planning, investment, and policy decisions for sustainable minigrid deployment in remote and environmentally sensitive regions.

Keywords: Minigrid, Photovoltaic Generation, Battey Storage, Energy Transition

1. Introduction

The Brazilian Amazon, covering 59% of the Brazilian territory and home to nearly three million people in remote and dispersed communities, still relies heavily on isolated minigrids powered by diesel generators. This diesel dependence, accounting for approximately 78% of the region's electricity supply, imposes significant logistical, economic, and environmental challenges (EPE, 2025; ONS, 2024).High fuel transportation costs, price volatility, and the environmental problems of combustion-based generation underscore the urgency of transitioning to cleaner and more resilient energy systems suited to the Amazonian context.

Hybrid renewable energy systems (HRES), typically integrating photovoltaic generation (PV), battery energy storage systems (BESS), and diesel gensets—have emerged as a viable alternative for off-grid electrification (Costa and Villalva, 2020; Martinez-Bolaños et al., 2020; Tabora et al., 2021). These systems have proven technically feasible, cost-effective, and capable of reducing emissions when properly designed. However, most studies focus on configurations with moderate renewable shares (60–80%) (Santos et al., 2024). There is limited research on the operational and economic implications of pushing renewable penetration beyond 90%, especially in medium-sized Amazonian communities with heterogeneous demand profiles and challenging operational conditions.

Achieving very high renewable shares introduces complex technical constraints. Isolated systems must balance supply and demand in real time without external backup, a challenge amplified by seasonal load variation, limited demand forecasting, and population dynamics (Haghighat Mamaghani et al., 2016; Santos et al., 2024). Moreover, solar intermittency and limited storage capacity often increase reliance on diesel as a buffer. Near-total renewable operation thus demands highly accurate forecasting and system optimization, which are frequently hindered by limited historical and high-resolution data (De Freitas Moscardini Júnior and Rüther, 2020; Rodriguez et al., 2024).

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This study investigates the technical and economic limits of reducing diesel dependency in isolated minigrids with renewable energy shares ranging from 90% to 100%. We hypothesize that size requirements, particularly for PV and BESS, increase non-linearly as diesel use is minimized, resulting in diminishing cost-effectiveness at very high renewable penetrations.

To test this hypothesis, we simulate PV+BESS+Genset hybrid systems using the HOMER Pro®, informed by real meteorological and load data from three Brazilian sites: Fernando de Noronha, Tefé, and Iauretê. These locations were selected for their diverse climate, solar irradiance, and demand profiles, enabling a robust comparative analysis. All scenarios assume uninterrupted power supply throughout the simulation period.

By grounding the analysis in real-world conditions and community-specific data, this work contributes to the broader debate on Brazil's energy transition in isolated areas. The findings aim to support policy, infrastructure planning, and investment strategies that accelerate decarbonization while enhancing energy access in the Amazon and similarly remote regions worldwide.

2. Methodology

The methodological approach comprises three main stages: community selection and data acquisition, techno-economic modeling, and comparative analysis.

2.1 Community Selection and Data Acquisition

Three Brazilian communities, Fernando de Noronha, Tefé, and Iauretê, were selected based on their contrasting climatic conditions, solar irradiance levels, and electricity consumption profiles (Figure 1). Energy demand data and technical specifications were collected from the Portal for Monitoring and Information on Isolated Systems (PASI) (EPE, 2025).

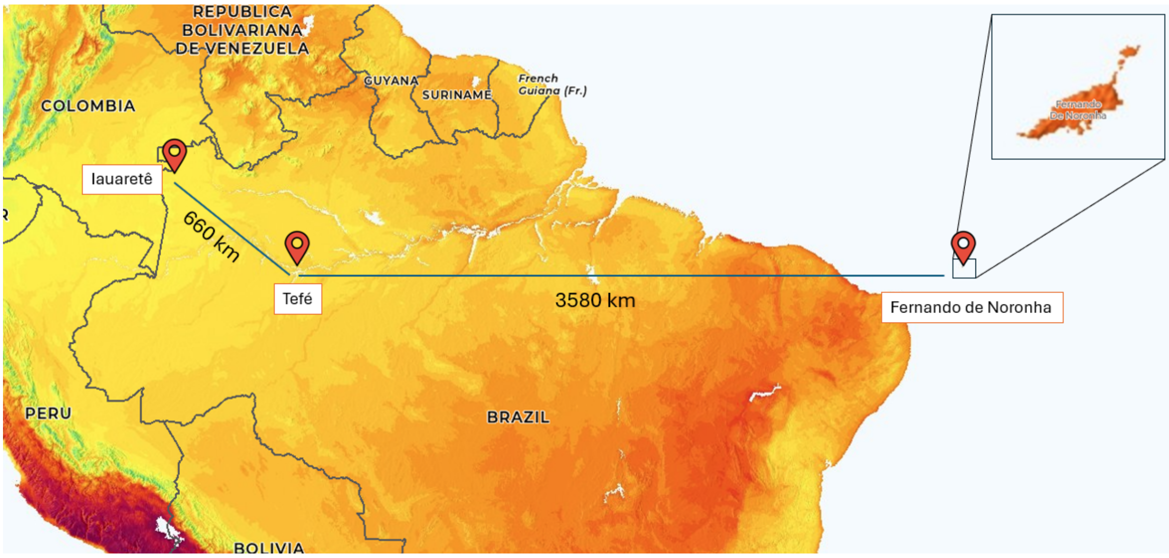

Figure 1 – Selected Brasilian communities

Figure 1 presents the irradiance map highlighting the selected communities. This map also allows for the observation of the distances between them. Notably, Fernando de Noronha has a GHI of approximately 2159 kWh/m², while Tefé and Iauretê have 1823 kWh/m² and 1689 kWh/m², respectively. Furthermore, the communities are geographically distant, with Fernando de Noronha located over 3500 km away from both Tefé and Iauretê, exhibiting significantly different environmental and climatic characteristics.

2.2 Modeling Approach and Simulation Parameters

Hybrid energy systems integrating PV, BESS, and diesel gensets were modeled using HOMER Pro®. Each system configuration was simulated across a range of RF targets, from 90% to 100%.

PV generation capacity was parametrized as a multiple of each community's peak demand. For instance, in

Fernando de Noronha, a PV system sized to 100% corresponds to approximately 4.7 MWp.

BESS capacity was defined in discrete steps, expressed in terms of hours of load coverage. This was calculated by dividing the total annual energy consumption by 8,760 (hours per year). For example, a 1-hour BESS configuration in Fernando de Noronha corresponds to approximately 3.3 MWh.

Diesel gensets were modeled with flexible capacity up to 100% of each community's peak demand, and without a minimum load constraint. This allows greater operational flexibility and enables future optimization of genset sizing according to the selected RF targets and dispatch criteria.

Each community was simulated using a PV+BESS+genset architecture, with the BESS operating as the grid-forming unit. The genset was allowed to disconnect entirely when renewable sources were sufficient to meet the load. The dispatch strategy prioritized renewable generation, and simulations were used to quantify the achievable RF under different PV and BESS combinations.

Simulation outputs included detailed datasets describing the achieved RF for each configuration. These were visualized using heatmaps to illustrate the technical feasibility and operational boundaries of each system design.

2.3 Techno-Economic Evaluation

To identify cost-optimal configurations, the model incorporated capital expenditures (CAPEX) and operational expenditures (OPEX) based on current commercial benchmarks for PV and BESS technologies [REF GREENER]. The Levelized Cost of Energy (LCOE) was calculated for each scenario to support cost-performance analysis under high-renewable penetration.

Special attention was given to critical RF thresholds (90%, 99%, 99.5%, 99.9%, and 100%) to characterize the incremental infrastructure and cost requirements for achieving near- or fully renewable operation.

2.4 Comparative Analysis Across Communities

A final comparative analysis was conducted to evaluate whether the relationships between PV size, BESS capacity, and RF exhibit consistent patterns across communities with differing solar resources, geographic constraints, and load profiles. This step aims to assess the generalizability of the findings and provide practical insights for designing high-renewable minigrids in remote and diverse contexts.

3. Results

The geographic locations of each community are shown in Figure 2 (Fernando de Noronha), Figure 3 (Tefé), and Figure 4 (Iauretê), along with their respective annual load profiles. The analysis reveals substantial variability in energy demand profiles across the three locations. Fernando de Noronha, a medium-scale oceanic island, exhibits a peak demand of approximately 5 MW. Tefé, a large Amazonian city with substantial seasonal load variation, reaches a peak of 20 MW, making it one of the largest isolated communities in the Brazilian SISOL system without plans for interconnection. In contrast, Iauretê, a small indigenous village in the remote upper Rio Uaupés region, presents a significantly lower peak demand, slightly above 200 kW. These contrasting conditions provide a robust foundation for understanding how system scale and load profiles influence the design requirements of high-renewable microgrids.

Simulation results show that reaching a 90% RF is technically viable across all communities with moderate system sizing. However, increasing the RF beyond this threshold results in a sharp and nonlinear escalation in infrastructure requirements, especially for energy storage. For Fernando de Noronha, the RF contour map shows the combinations of PV and BESS capacities capable of achieving RF levels from 90% up to 100%. As the contour lines indicate, moving from 90% to 99% RF demands a 20% increase in PV capacity and a 78% increase in BESS capacity. Pushing further to 99.5% requires an additional 6% in PV and 55% in BESS. To reach 99.9%, a 40% increase in PV and 84% in BESS are needed, and achieving 100% RF ultimately requires a cumulative increase of 89% in PV and 228% in BESS compared to the 90% scenario. In absolute terms, this corresponds to a total installed capacity of 31.4 MWp of PV and 195.8 MWh of storage, as shown in Figure 5.

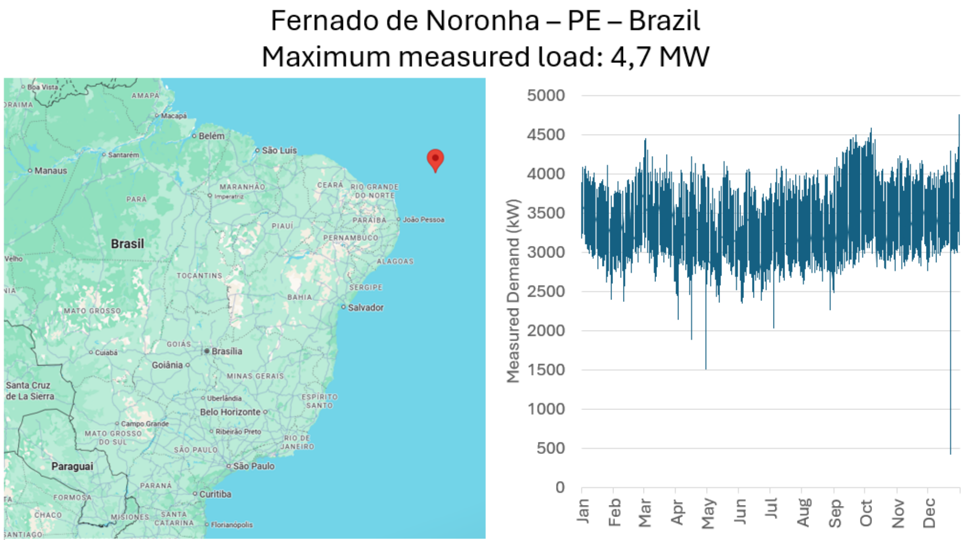

Figure 2 - Fernando de Noronha geographic location and annual load profile.

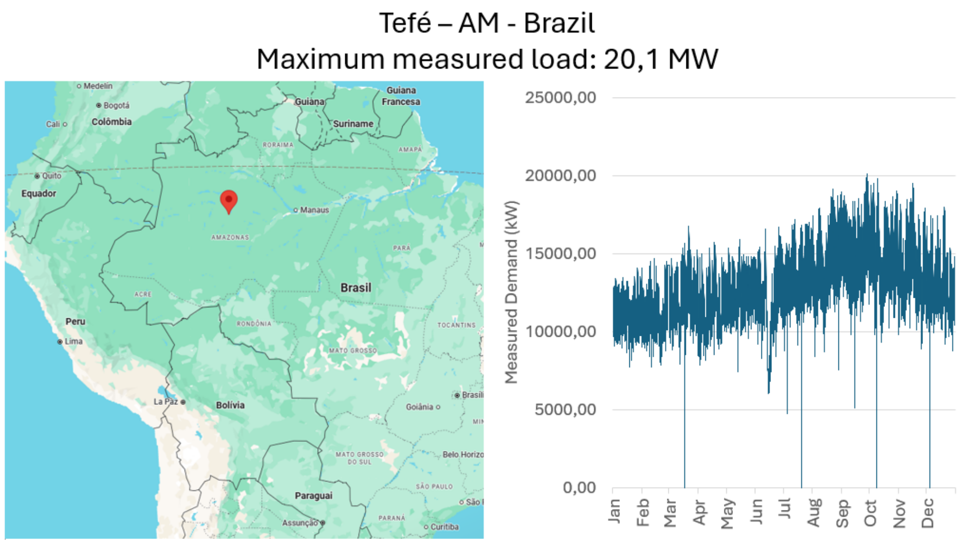

Figure 3 - Tefé geographic location and annual load profile.

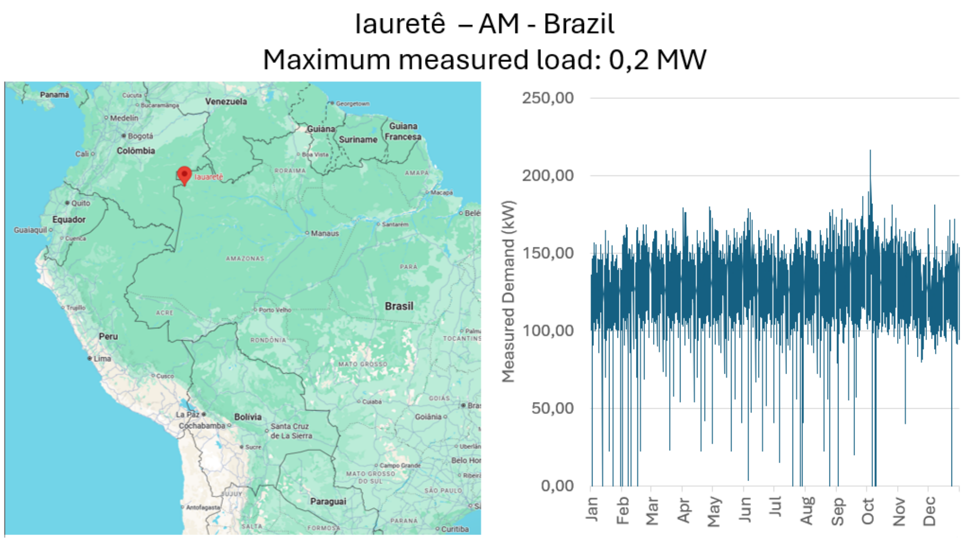

Figure 4 - Iauretê geographic location and annual load profile.

In Tefé, the trend is even more pronounced due to the larger load and more complex seasonal consumption profile. The RF contour map for Tefé, highlights the significant infrastructure expansions required to increase RF. Moving from 90% to 99% RF requires a 42% increase in PV and 142% in BESS capacity. To reach 99.5%, an additional 10% PV and 16% BESS are required. The transition from 99.5% to 99.9% calls for another 11% in PV and 67% in BESS. Finally, the shift from 99.9% to 100% demands a further 14% increase in PV and 13% in BESS. Altogether, this represents a cumulative 77% increase in PV and 238% in BESS compared to the 90% baseline, corresponding to 179.7 MWp of PV and 1046.2 MWh of storage, as detailed in Figure 6.

Iauretê, despite its much smaller scale, exhibits a similar pattern. The RF contour map for Iauretê, (Figure 7). From 90% to 99% RF, PV capacity must increase by 35% and BESS by 123%. Moving to 99.5% adds another 17% in PV and 12% in BESS, while the jump to 99.9% requires 24% and 73%, respectively. Reaching 100% renewable supply from this point requires a final increase of 9% in PV and 38% in BESS. Overall, the transition from 90% to 100% RF in Iauretê demands 85% more PV and 246% more BESS capacity. In absolute terms, the system must scale from 0.99 MWp and 3.3 MWh to 1.84 MWp and 11.4 MWh.

These incremental changes are quantitatively summarized in Table 1, which presents the percentage increase in PV and BESS capacity required to move from 90% RF to each higher target for the three communities. Table 2 presents the absolute values of installed PV power and BESS energy capacity required to meet each RF level. These two tables collectively demonstrate the technical challenges of pursuing full renewable coverage, especially in systems with high variability and isolated supply.

Table 1 - Incremental increases in PV and BESS capacities required to achieve each RF for the analyzed communities from 90% of RF

	Fernando de Noronha - PE		Tefé - AM		Irauretê - AM	
	PV	BESS	PV	BESS	PV	BESS
99.0%	20%	78%	42%	142%	35%	123%
99.5%	26%	133%	52%	158%	52%	135%
99.9%	66%	217%	63%	225%	76%	208%
100.0%	89%	228%	77%	238%	85%	246%

Table 2 - Installed PV power values and BESS energy capacity for service at each RF level

	Fernando de Noronha - PE		Tefé - AM		Irauretê - AM	
	PV (MWp)	BESS (MWh)	PV (MWp)	BESS (MWh)	PV (MWp)	BESS (MWh)
90.00%	15.7	59.7	101.5	310.0	0.99	3.3
99.00%	20.0	106.2	143.7	749.1	1.34	7.3
99.50%	24.3	152.6	154.3	800.8	1.51	7.7
99.90%	27.6	189.1	164.9	1007.5	1.75	10.1
100.00%	31.4	195.8	179.7	1046.2	1.84	11.4

Finally, per capita system sizing further highlights differences across contexts. At 90% RF, Fernando de Noronha requires approximately 5 kWp of PV and 18 kWh of BESS per inhabitant. Tefé, with its larger economy of scale, needs only 1.3 kWp of PV and 4.2 kWh of BESS per capita. Iauretê, despite its lower overall load, has higher per capita needs: 1.8 kWp of PV and 6.3 kWh of BESS. At 100% RF, these values double or triple—reaching 10 kWp PV / 61 kWh BESS for Fernando de Noronha, 2.4 kWp PV / 14.1 kWh BESS for Tefé, and 3.4 kWp PV / 21.6 kWh BESS for Iauretê.

These results provide a clear and quantifiable illustration of the "last-mile" cost problem in renewable energy integration. The final increments toward 100% renewable penetration impose disproportionately high storage and generation costs, regardless of system scale. This underscores the importance of carefully evaluating trade-offs between technical feasibility, economic efficiency, and energy autonomy when designing resilient, low-carbon energy systems for remote or isolated communities.

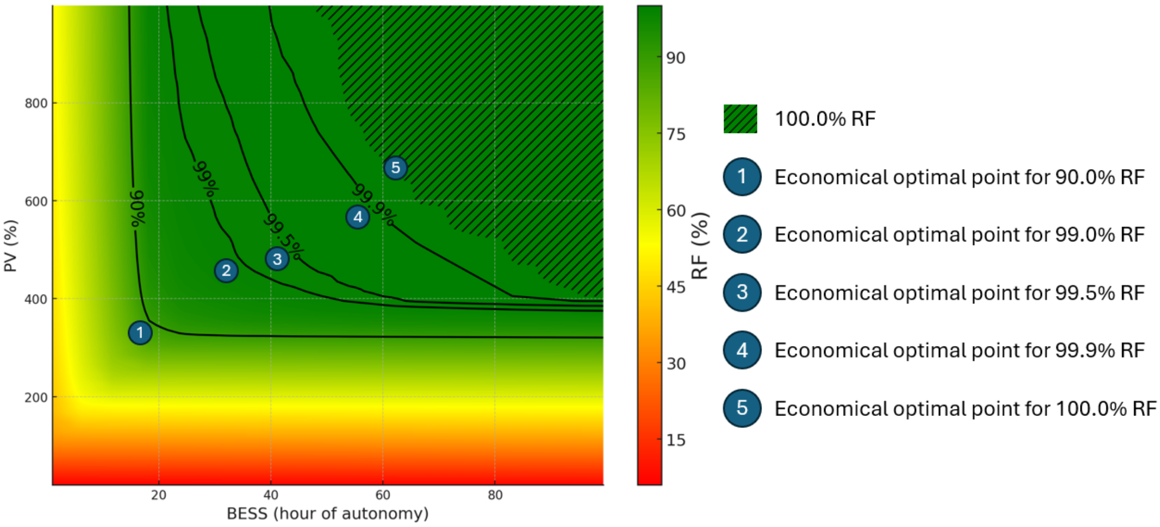

Figure 5 - Renewable Fraction Contour Map: Fernando de Noronha – PE

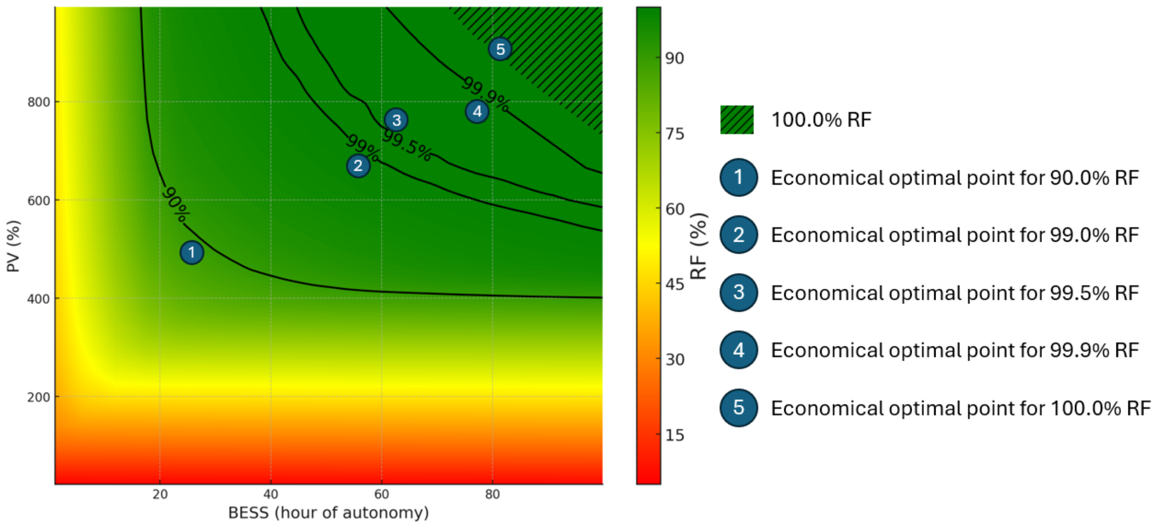

Figure 6 - Renewable Fraction Contour Map: Tefé – PE

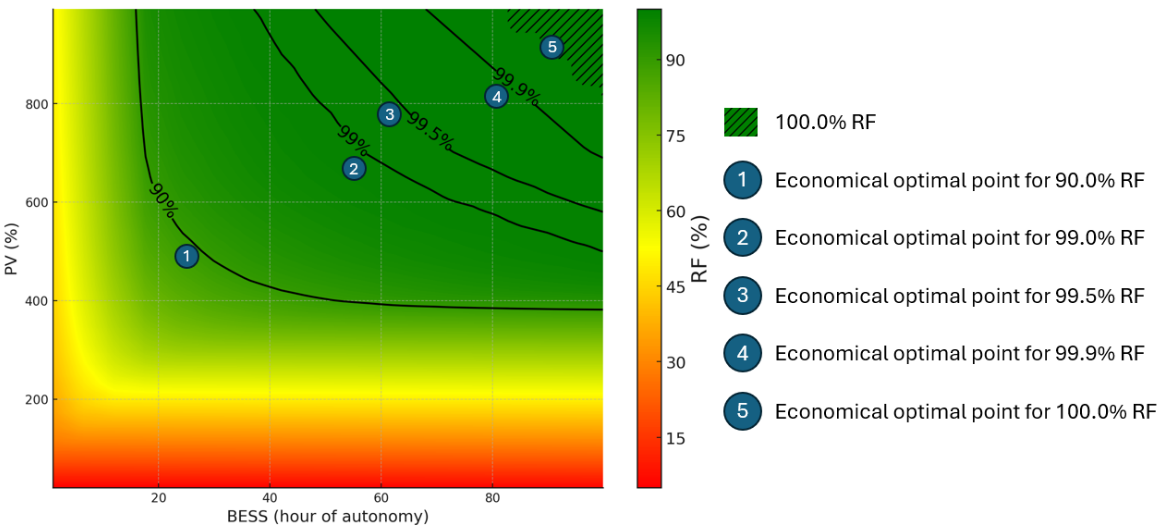

Figure 7 - Renewable Fraction Contour Map: Iauretê - AM

4. Discussion

Despite the markedly different characteristics of Fernando de Noronha, Tefé, and Iauretê, including significant variations in solar irradiance (GHI), load profiles, and geographic isolation, our simulations revealed a remarkably consistent pattern in the relationship between RF and system sizing across all three sites. This suggests that, even in highly diverse contexts, the technical behavior of isolated hybrid systems aiming for 100% renewable energy penetration is largely predictable. This insight has important implications for energy planning in remote areas of Brazil and other regions with similar logistical and environmental constraints.

The most significant barrier to achieving full renewable penetration is the extreme oversizing required for both PV and BESS. Due to the intermittency of solar generation and demand variability, systems must be sized to operate independently even during prolonged periods of low insolation or high load. This leads to exponential increases in infrastructure requirements as RF approaches 100%. On average, moving from 90% to 100% RF required an 83% increase in PV capacity and a 237% increase in BESS capacity. In practical terms, this means doubling PV and tripling BESS compared to a 90% RF baseline.

These requirements translate into substantial system sizes: 31.4 MWp for Fernando de Noronha, 179.7 MWp for Tefé, and 1.84 MWp for Iauretê. Such expansions raise questions regarding land availability, environmental licensing, and the logistical complexity of deployment, especially in ecologically sensitive or geographically inaccessible regions like the Amazon. Although this study did not include detailed capital expenditure (CAPEX) analysis, the scale of infrastructure required and Brazil's high cost of capital indicate that 100% RF systems may be economically unfeasible without targeted financing mechanisms or subsidies.

Environmental impacts of large-scale PV and BESS deployment were also beyond the scope of this work, but deserve further attention. Mechanisms such as avoided emissions compensation could increase the financial viability of high-renewable microgrids, while supporting Brazil's broader decarbonization objectives.

Another critical insight is the need for long-duration energy storage. Battery-based solutions face cost and scalability limitations, especially beyond 90% RF. Complementary renewable energy vectors, such as sustainable biofuels or green hydrogen, may offer viable alternatives for seasonal storage or firm capacity. Our results also support the development of a phased national roadmap for decarbonizing Brazil's isolated power systems. While full renewable penetration may be unrealistic in the short term, intermediate targets above the current 22% renewable share are both technically feasible and economically attractive. Notably, the lowest LCOE values in our study occurred at RF levels above 80%.

5. Conclusion

This study evaluated the technical and economic feasibility of achieving high renewable energy penetration in isolated Brazilian microgrids through simulations of PV+BESS+diesel hybrid systems in three contrasting communities: Fernando de Noronha, Tefé, and Iauretê. Despite significant differences in scale, solar resource availability, and load profiles, all systems exhibited a consistent and nonlinear relationship between the RF and the required infrastructure sizing, particularly for BESS.

The results confirm that while achieving 90% RF is technically and economically viable with moderate scaling of PV and BESS, pursuing near-total renewable coverage (approaching 100%) demands disproportionate increases in system capacity. On average, reaching 100% RF required 83% more PV and 237% more BESS than at 90% RF. These steep requirements imply higher land use, elevated capital investments, and increased logistical complexity, especially in remote and environmentally sensitive areas such as the Amazon.

Although technically achievable, 100% renewable operation is not broadly applicable under current economic and policy conditions. The sharp escalation in costs and infrastructure associated with the final 10% of decarbonization illustrates the well-known "last-mile" problem in energy transitions. Our simulations showed that the most cost-effective configurations occurred between 80% and 90% RF, indicating this range as a pragmatic target for near-term investment and policy planning.

Therefore, rather than aiming universally for 100% renewable systems, energy transition strategies in isolated regions should prioritize economically optimal renewable shares up to 90%, while addressing the remaining demand through flexible and locally adapted solutions. Promising options include green hydrogen, sustainable biofuels, or other long-duration storage technologies suited to local resource availability and operational constraints.

To advance this transition, future work should integrate environmental impact assessments, policy frameworks for emission compensation, and innovative financing mechanisms that reflect the realities of high-capital-cost environments like Brazil. Public-private partnerships and incentive schemes can also help scale these systems while ensuring energy security and sustainability.

In summary, high-renewable PV+BESS microgrids represent a robust pathway for decarbonizing isolated systems, but full renewable autonomy remains economically prohibitive in most cases. A phased, flexible, and context-sensitive approach is essential to balance energy access, resilience, and carbon reduction in remote communities across Brazil and beyond.

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