HYBRID POWER PLANTS IN ISOLATED SYSTEMS IN THE AMAZON: THE CASE OF THE CITY OF TEFÉ

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Overview

The transition to sustainable energy systems is a pressing global challenge, particularly in regions with unique geographical and infrastructural complexities such as the Amazon Basin. Tefé-AM, located in Northern Brazil and home to approximately 60,154 inhabitants, is one of the most significant urban centers in the Amazon region due to its strategic location along the Solimões River. As a regional hub, Tefé provides essential public services, education, and healthcare, serving not only its population but also the surrounding rural and riverine communities. Additionally, the city is a gateway to the Mamirauá Sustainable Development Reserve, a UNESCO-designated natural heritage site, further underscoring its importance in promoting ecotourism and environmental conservation in the Amazon. Despite its vital role in regional development, Tefé's energy system remains heavily reliant on diesel-powered thermoelectric plants, resulting in high operational costs, significant greenhouse gas emissions, and vulnerabilities in energy supply. Addressing these challenges requires innovative solutions that balance energy security, economic feasibility, and environmental sustainability. This study explores the feasibility of transitioning Tefé's energy system toward a hybrid model integrating renewable energy sources, storage technologies, and natural gas. Using the urbs linear optimization framework, various scenarios were simulated, including combinations of diesel, photovoltaic (PV) systems, battery storage, and natural gas. Key metrics such as levelized cost of electricity (LCOE), CO_2 emissions, and investment requirements were evaluated to determine the most effective configuration. The results reveal that hybrid systems can significantly reduce costs and emissions while enhancing energy reliability. The integration of solar PV and batteries demonstrates substantial potential to decrease diesel dependency, while natural gas serves as a transitional fuel to further improve supply stability. These findings provide a replicable model for isolated systems across Brazil and globally, contributing to the broader energy transition.

Methods

This study employed the urbs energy modeling framework, a robust open-source tool designed for optimizing distributed energy systems. Developed by the Technical University of Munich, urbs uses linear programming to analyze energy flows, infrastructure investments, and operational trade-offs (Dorfner, 2023). Its flexibility allows for detailed evaluations of scenarios, including exclusive diesel reliance, integration of solar PV, solar PV with battery storage, hybrid systems incorporating natural gas, and fully renewable configurations. By quantifying costs, emissions, and system reliability, urbs offers valuable insights into sustainable energy transitions.

Key inputs included normalized hourly demand data derived from ONS's regional load curve and scaled to match Tefé's average consumption of 19.8 MW. Solar PV generation was simulated using Renewable Ninja, yielding a 14% capacity factor and 1,226 full-load hours annually (Pfenninger & Staffell, 2016). Techno-economic parameters, such as investment costs and operational data, were sourced from the World Energy Outlook and NREL reports. Fuel costs were estimated at R$ 8.05/L for diesel, equivalent to USD 138.71 per MWh thermal (Teixeira, 2023), and R$ 7.00/m³ for natural gas, equivalent to USD 121.95 per MWh thermal (Cigás, 2024). These inputs enabled a robust analysis of cost and performance for the energy scenarios modeled. The *urbs* model optimized energy generation, storage, and supply while considering constraints such as fuel logistics, emissions, and seasonal solar variability. Diesel transportation via waterways, battery efficiency, and emissions from fossil fuel combustion were key factors integrated into the optimization.

Results

Results highlighted installed capacities for each scenario, as shown in Figure 1 (a), and provided a detailed analysis of the Levelized Cost of Electricity (LCOE) for different configurations (Figure 1 (b)). The LCOE findings demonstrated that hybrid systems integrating solar PV and battery storage could achieve substantial cost reductions compared to diesel-only systems, underscoring the economic feasibility of transitioning to renewable energy solutions. The optimization results illustrate the transformative potential of hybrid energy systems for isolated systems such as Tefé-AM. The current diesel-only system generates approximately 174 GWh annually, with significant CO_2 emissions of 120 ktons/year. Integrating solar PV reduces diesel dependence, cutting emissions by 33%, while scenarios including battery storage achieve up to 95% emission reductions. The fully renewable PV+Batteries scenario eliminates CO_2 emissions entirely but involves higher curtailment due to overproduction.

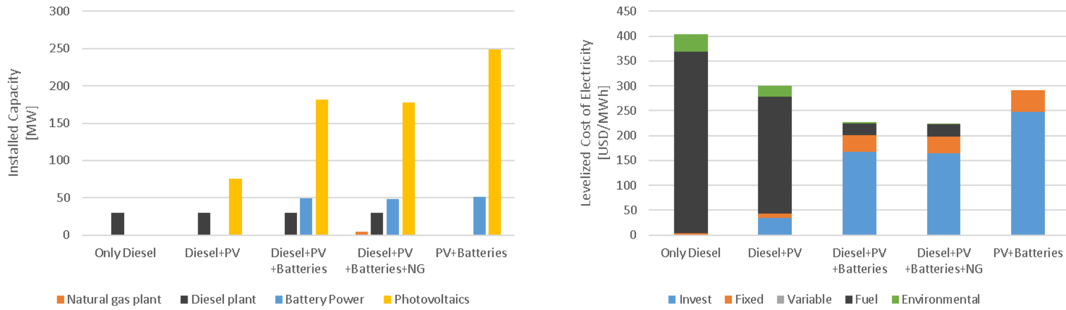

Figure 1: (a) Installed capacities in the different scenarios (b) Levelized Cost of Electricity of the different scenarios. Source: own elaboration.

Figure 2 (a) illustrates electricity generation and consumption across scenarios, showcasing increased PV integration and reduced diesel and natural gas reliance. While the PV+Batteries scenario has the highest investment costs, these are offset by lower operational expenses. Hybrid scenarios achieve the lowest Levelized Cost of Electricity (LCOE), combining economic viability with environmental benefits. Figure 2 (b) highlights annual CO_2 emissions, demonstrating the significant environmental gains of adopting hybrid and renewable systems. These results emphasize the potential for cost reduction, improved reliability, and sustainable energy development in isolated systems like Tefé.

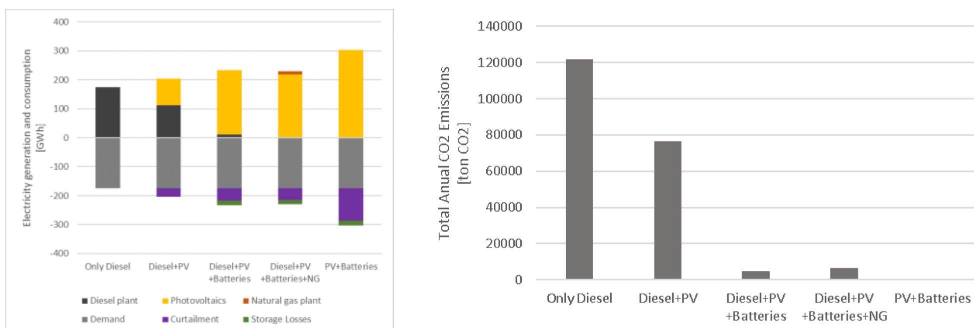

Figure 2: (a) Yearly electricity generation and consumption (b) Total anual CO_2 Emissions . Source: own elaboration.

Conclusions

This study highlights the potential of hybrid energy systems to transform isolated regions like Tefé-AM. Integrating solar PV and battery storage reduces diesel dependency, lowers CO_2 emissions, enhances energy reliability, and stabilizes costs. Scenario 4 (Diesel + PV + Batteries + Natural Gas) proved the most cost-effective, achieving the lowest Levelized Cost of Electricity (LCOE) with minimal upfront investment, balancing flexibility with significant emission reductions. The results confirm that renewable integration is technically and economically viable, offering a replicable model to advance energy transitions in remote regions, supporting climate goals and improving living standards.

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