



Evaluating off-grid energy solutions for rural demand in Brazil – a case study

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Abstract: Recently, Electrical energy enables the operation of machinery, heat generation, and information transmission. This energy is generated, transmitted, and distributed until it reaches the end consumer; however, interruptions in the power supply pose significant challenges, especially for rural producers in the state of Goiás, who face losses such as food spoilage and the death of animals in breeding facilities. With the advancement of distributed generation, consumers are increasingly able to produce their own energy, becoming prosumers. This study presents a case analysis of a rural property located in Cezarina, Goiás, Brazil, aiming to identify the most suitable solution for ensuring a reliable energy supply through alternative generation sources. Three scenarios are evaluated: (1) Grid Electricity + Backup Generator, (2) Grid Electricity + Off-Grid Photovoltaic System, and (3) Grid Electricity + Off-Grid Photovoltaic System + Battery Storage. Based on the property's energy demand, equipment is dimensioned for each configuration, and a financial analysis is conducted using key indicators such as Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback Period, and Levelized Cost of Energy (LCOE). The results indicate that the "Grid Electricity + Off-Grid Photovoltaic System + Battery Storage" scenario presents the best overall feasibility. Although it requires an initial investment nearly nine times higher than the traditional "Grid Electricity + Backup Generator" configuration, it offers a lower LCOE and demonstrates greater long-term financial and operational advantages over a 30-year analysis horizon.

Keywords: photovoltaic systems, diesel generators, hybrid systems, power outage mitigation, financial analysis.

1 Introduction

In rural areas, access to reliable electricity remains a key driver of socioeconomic development and technological integration. Due to its ability to be transmitted over long distances and converted into various forms—such as light, heat, and mechanical power—electricity plays a central role in rural development strategies (Villalva 2012; Slough et al. 2015; Quispe et al. 2024; Wahby et al. 2025). However, despite the extensive deployment of distribution networks in Brazil, significant portions of remote rural regions still face limited access to electricity, primarily due to the high logistical and financial costs of infrastructure expansion (Slough et al. 2015; Perez-Sebastian et al. 2020; Das et al. 2022).

The Brazilian electric power matrix is composed of both renewable sources—such as hydro, biomass, wind, and solar—and non-renewable ones, including natural gas, nuclear energy, petroleum derivatives, and coal. Among these, hydroelectric power stands out as the dominant source, supplying 56.8% of the country's electricity (EPE 2024). This matrix is largely based on a centralized generation model, in which electricity is produced in specific locations and then transmitted across long distances to consumers. While effective on a national scale, this approach often proves inefficient for rural and isolated areas due to its vulnerability to supply interruptions and its dependence on complex infrastructure (Slough et al. 2015; Perez-Sebastian et al. 2020; Jean et al. 2021).

In response to these limitations, Brazil has increasingly promoted distributed generation, a model in which electricity is produced close to the point of consumption. Within this context, photovoltaic solar

energy has emerged as the most prominent technology, accounting for 88.3% of distributed generation in 2024 (EPE 2024). Grid-connected photovoltaic systems have proven essential for decentralizing electricity generation, enhancing supply resilience, and reducing dependency on traditional utility providers. Moreover, they help to mitigate the seasonal variations of hydroelectric generation that often influence electricity tariffs (Maestri and Andrade 2022; da Silva and Rato 2024). Consumers who generate and consume their own energy under this model are referred to as prosumers.

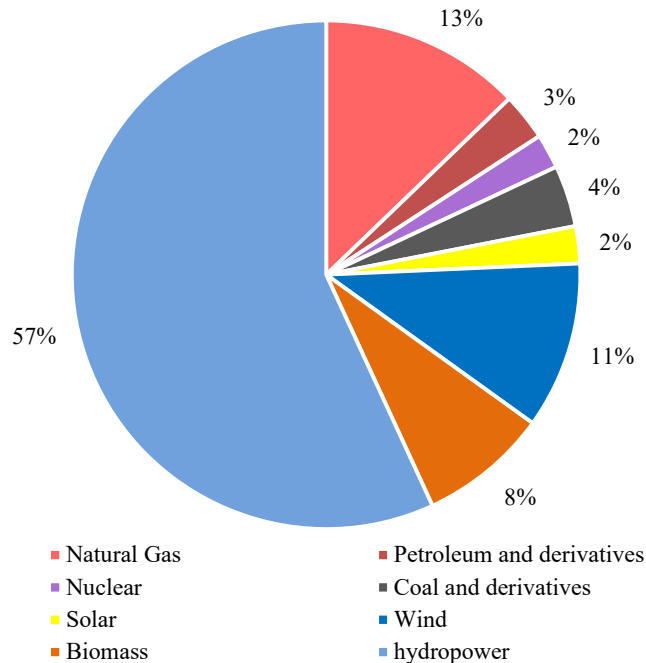


Figure 1. Percentages of energy generation in Brazil (EPE 2024).

Photovoltaic systems have a wide range of applications, including grid-connected systems that help reduce electricity costs by directly lowering energy bills, stand-alone systems for areas without access to the power grid, and hybrid systems designed for locations connected to the grid but experiencing intermittent power supply. For both stand-alone and hybrid systems, energy storage solutions—such as batteries—can be utilized to ensure continuous electricity availability during periods of insufficient solar radiation (Pinho and Galdino 2014; González-Rivera et al. 2020; Li et al. 2025).

In many industries, diesel-powered generator sets (gensets) are used as an alternative to maintain continuous production and minimize losses. However, while the initial cost of diesel gensets may be relatively low, their use significantly increases operational expenses and contributes to environmental pollution due to emissions (Salas et al. 2015; Babajide and Brito 2021; Samatar et al. 2025). Given these challenges, it becomes essential to explore alternative energy solutions that provide improved efficiency and economic viability, particularly in light of increasing sustainability concerns (Brandi and dos Santos 2020; Yuksel et al. 2024; Li et al. 2025).

The primary objective of this study is to evaluate the most technically and economically viable solution among various configurations of hybrid photovoltaic systems and diesel gensets, aiming to mitigate the impacts caused by power outages (Rodrigues, 2016). The case study will focus on a property in a rural area of Goiás, Brazil, with specific goals of identifying alternative distributed generation sources that can reduce or replace the reliance on diesel gensets—currently the main energy source in rural areas to ensure uninterrupted electricity supply—and, in doing so, lower fuel costs and reduce pollutant emissions.

The exploration of hybrid energy systems—particularly those combining photovoltaic (PV) generation with diesel gensets—has become a recurring theme in recent literature addressing energy access and reliability challenges, especially in remote or off-grid regions. Many studies apply techno-economic analyses, frequently using simulation tools such as HOMER, to evaluate optimal system configurations. For example, research conducted in Nigeria demonstrated that although PV-diesel hybrid systems entail higher initial investments compared to PV-only mini-grids, they provide superior reliability, ensuring 100% energy availability (Akinyele 2018). Similar analyses using HOMER have been employed to optimize standalone residential systems in urban India, integrating PV, wind, diesel, and battery storage (Pask et al. 2017; Kumar and Tewary 2022), as well as to minimize costs and emissions in rural off-grid systems that

include wind energy (Dinesh and Sawle 2022). More complex industrial applications, such as those in tea processing plants, have also been modeled—considering both grid-connected and isolated options involving PV, biomass, hydro, and diesel generation—highlighting the economic benefits of grid integration and waste heat recovery (Thirunavukkarasu and Sawle 2022). In addition to conventional simulations, researchers are exploring advanced metaheuristic optimization algorithms, such as the Honey Badger Optimizer, to enhance the sizing of PV-battery-diesel systems in rural communities, potentially achieving lower total annual costs than traditional methods (Thirunavukkarasu et al. 2023). Performance evaluations conducted in regions like Algeria confirm that integrating PV into existing diesel infrastructure yields efficiency improvements and emission reductions, especially under conditions of high load and solar irradiance (Brahim 2019). Comparative reviews and case studies have also investigated PV-wind hybrid configurations, occasionally combining optimization methods like Particle Swarm Optimization (PSO) with HOMER to identify the most cost-effective and renewable-rich solutions based on indicators such as cost of energy (COE) and renewable energy fraction (Sawle et al. 2018). Furthermore, the field is gradually expanding to incorporate broader perspectives beyond strictly techno-economic metrics, recognizing the need for modeling tools that also consider social factors—such as health, education, and long-term sustainability—as critical components in the design of rural energy systems (Natividad and Benalcazar 2023). Collectively, this body of research emphasizes the importance of context-specific analysis and system optimization, while consistently highlighting PV-diesel hybrid configurations, often supported by battery storage, as a technically and economically viable strategy to enhance energy security and reduce dependence on fossil fuels in underserved regions (Loeza-Mejía et al. 2025).

2 Theoretical framework

This chapter presents the main literature references related to distributed generation, through the contextualization of this concept within the Brazilian electric power matrix. It aims to highlight the primary applications currently under study, namely: grid-connected (on-grid) and stand-alone (off-grid) photovoltaic systems, battery energy storage, diesel generator sets (gensets), and hybrid photovoltaic systems.

2.1 Distributed generation (DG) and photovoltaic systems

Most of Brazil's electricity generation is centralized, primarily through large hydroelectric and thermoelectric power plants, which are typically located far from urban centers. As a result, electricity is transmitted over long distances to consumers through transmission lines and distribution networks (Lucas De Souza and Bandeira De Mello 2018; Jean et al. 2021).

In recent years, the country has increasingly diversified its energy matrix, focusing on renewable sources due to the abundance of natural resources. In addition to hydropower, the country's high levels of solar irradiation have stimulated the growth of photovoltaic solar energy, while favorable wind patterns in the northern regions have supported the development of wind energy (Lucas De Souza and Bandeira De Mello 2018; EPE 2024).

The use of distributed generation (DG) in Brazil has been growing steadily, driven by the benefits it offers both to consumers and to the electrical system. DG reduces transmission and distribution losses, which are more significant due to the long distances between generation and consumption points. Additionally, DG enhances system stability and can influence electricity tariffs set by utility companies (Lucas De Souza and Bandeira De Mello 2018; Costa et al. 2019).

Within this context, photovoltaic systems have become the most widely used technology for distributed generation. Their widespread availability, low operational costs, and the ongoing reduction in photovoltaic technology prices makes them an ideal choice. Furthermore, solar systems can be easily integrated into residential, commercial, and industrial settings, making them a prime candidate for decentralized energy production. Photovoltaic systems can either be connected to the grid or operate independently. On-grid systems allow energy exchange between the consumer and the utility, while off-grid systems function autonomously, disconnected from the power grid (Villalva 2012; Ortega-Arriaga et al. 2021; Rynska 2022). Figure 2 illustrates the connection schemes and main components of both on-grid and off-grid photovoltaic systems.

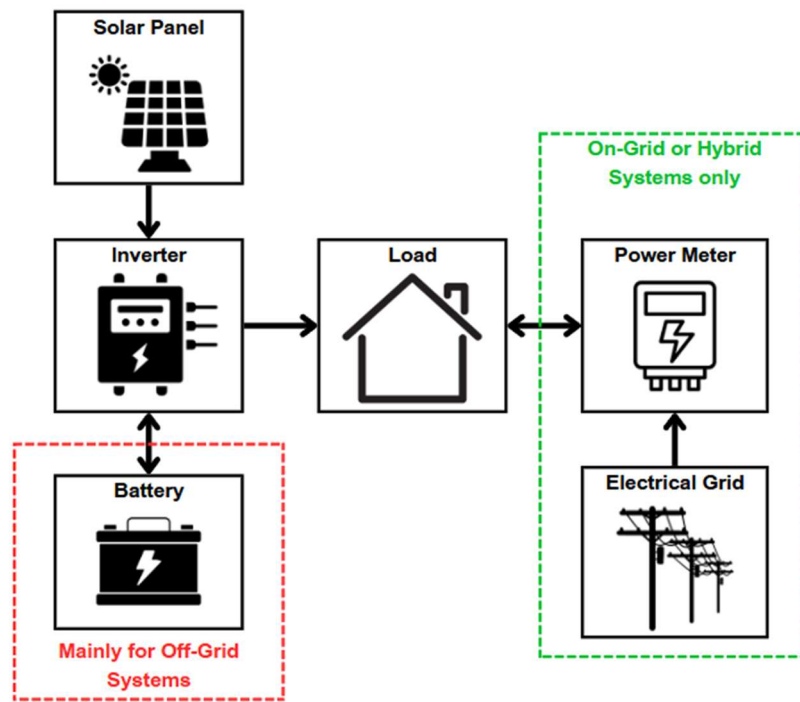


Figure 2. On-grid and off-grid Photovoltaic representation.

The photovoltaic solar panel, also known as a photovoltaic module, is the component responsible for converting solar irradiation into electrical energy through the photovoltaic effect. These panels are typically made of semiconductor materials, with monocrystalline and polycrystalline silicon being the most commonly used technologies on the market (Ferreira et al. 2018; David et al. 2021).

The electricity produced by the panels is in the form of direct current (DC) and must be converted into alternating current (AC) to be compatible with the power grid and standard electrical loads. This conversion is carried out by inverters, which are classified as on-grid or off-grid depending on the system configuration. On-grid inverters adjust the electricity generated to match the voltage, current, and frequency standards of the public utility grid, enabling seamless integration of photovoltaic systems into the distribution network. These devices typically have an operational lifespan of 10 to 15 years and an average warranty period of around 5 years (Coutinho Gomes and Fernandes 2020).

In off-grid systems, which operate independently of the utility grid, off-grid inverters perform the same DC-to-AC conversion, typically supplying voltages of 127V or 220V to meet local energy demands. To regulate the charging and discharging of the battery bank in such systems, charge controllers are employed to monitor electrical parameters and extend battery life (Pinho and Galdino 2014; Loeza-Mejía et al. 2025). The batteries, which store energy in DC at voltages of 12V, 24V, or 48V, ensure continuous energy supply during periods of low solar irradiation. Common battery technologies used include lead-acid, nickel-cadmium, lithium iron phosphate, and lithium-ion (Babbitt 2020; Pavković et al. 2024).

In grid-connected systems, a bidirectional energy meter installed by the utility company monitors the flow of electricity in both directions—recording the surplus energy injected into the grid after local consumption and the energy drawn from the grid when needed.

2.2 Battery energy storage system

Photovoltaic systems equipped with battery storage have been used in Brazil for several years, initially relying on lead-acid batteries to supply electricity to remote areas. A significant milestone in the adoption of these systems was the implementation of the Energy Development Program for States and Municipalities, which enabled the installation of more than 6,200 photovoltaic systems with lead-acid batteries in isolated communities (Greener and NewCharge 2021). These systems proved to be a viable solution for regions where extending the conventional electrical grid is economically or technically unfeasible (Salas et al. 2015).

In addition to their use in remote locations, battery-based photovoltaic systems are also applied in urban settings as auxiliary sources for energy savings. In these cases, they offer various benefits such as

financial returns, improved power quality, enhanced system stability, and increased reliability (Andrade et al. 2021, Oliveira et al, 2015).

Among the battery technologies used in photovoltaic applications, lead-acid batteries remain the most cost-effective in terms of energy storage cost per watt-hour. However, their performance is significantly affected by temperature, which can reduce both efficiency and lifespan. These batteries are most effective in environments where the ambient temperature does not exceed 25°C to 30°C (FERREIRA 2021). Their service life also varies according to their usage profiles, with their life cycle ranging from 500 to 2,500 cycles, and a depth of discharge varying from 60% to 70% (Costa et al. 2019; FERREIRA 2021; Rasul and Kim 2024).

Nickel-cadmium batteries, although around 5.24% more expensive than lead-acid batteries at initial purchase, offer several advantages: they require less maintenance, have a longer operational life, and are less sensitive to high temperatures. These batteries are suitable for environments with maximum temperatures between 35°C and 40°C and can achieve a service life of up to 4,000 cycles, with a depth of discharge varying from 80% to 100% (Rasul and Kim 2024; Alluraiah et al. 2024).

Lithium-ion batteries, in turn, provide superior performance compared to lead-acid batteries in terms of cycle life, achieving approximately 3,000 cycles at an 80% depth of discharge (Coppez et al. 2010). More recently, lithium iron phosphate batteries have been introduced, primarily for powering critical loads. These batteries stand out for their higher power capacity, enhanced performance, and extended lifespan—reaching over 10,000 cycles (Muslimin et al. 2022; Rasul and Kim 2024).

2.3 Diesel generator set (GMG)

The Diesel generator sets (GMGs) have long been a common solution for supplying electricity in isolated or underserved areas, offering quick deployment and operational autonomy. In Brazil, there are approximately 140,000 diesel generators in operation, reflecting their widespread use, especially in rural and remote regions where grid expansion is not technically or economically feasible. Despite their practicality, GMGs present significant long-term limitations. Their reliance on fossil fuels results in high operational costs, particularly in areas with difficult fuel logistics, and they require regular maintenance, which can reduce reliability and increase downtime (Gavrilaş and Neagu 2020; Yukizaki et al. 2023).

Beyond financial drawbacks, diesel generators pose serious environmental concerns. They emit substantial quantities of carbon dioxide (CO₂), nitrogen oxides (NO_x), and particulate matter, contributing to both local air pollution and global greenhouse gas emissions. This environmental footprint has heightened the urgency of finding cleaner and more sustainable alternatives (Costa et al. 2019; Babajide and Brito 2021).

In contrast, Brazil has seen rapid growth in the adoption of photovoltaic (PV) solar energy. As of recent data, the country hosts more than 2.4 million PV systems, primarily in distributed generation configurations. This expansion highlights a strong shift toward renewable sources, driven by falling technology costs, regulatory incentives, and the widespread availability of solar irradiation throughout the country (EPE 2024).

In this context, hybrid energy systems that combine diesel generators with photovoltaic solar power and battery storage have gained significant traction (Foo and Lam 2013). These systems optimize energy use by reducing diesel consumption, lowering emissions, and improving supply reliability. They also prolong the operational life of the diesel generator by minimizing its usage, especially during periods of high solar availability (Salas et al. 2015; Babajide and Brito 2021).

To design effective and sustainable energy solutions, it is essential to understand the technical and economic characteristics of each system configuration. Well-planned hybrid systems can offer lower energy costs, increased resilience, and reduced environmental impact—positioning them as a strategic alternative to the exclusive use of diesel generators in Brazil’s evolving energy landscape (Costa et al. 2019).

2.4 Hybrid electrical systems

In Brazil, most Diesel Generator set are installed in commercial and industrial facilities to ensure power supply during outages or in regions with unreliable grid access. With the rapid growth of photovoltaic technology, many of these establishments have adopted solar energy solutions alongside their existing GMGs. This evolution has led, in practice, to the emergence of hybrid energy systems, even if they were not originally designed as such. Motivated by the falling cost of photovoltaic modules and the growing demand for energy autonomy and sustainability, businesses are increasingly combining solar generation

with backup diesel systems and, in some cases, battery storage (da Ponte et al. 2021; Yukizaki et al. 2023). This trend has contributed to a more resilient and diversified energy landscape, reducing dependence on fossil fuels and improving the cost-effectiveness of electricity supply, especially during peak tariff periods or supply interruptions (Perez-Sebastian et al. 2020; Jia et al. 2024; Pawar et al. 2024).

A notable example is the study by Costa and Villalva (Costa et al. 2019), which evaluated an off-grid hybrid system implemented in the Tapajós-Arapiuns Extractive Reserve. The system combined a photovoltaic generator and a lead-acid battery bank as the primary energy source, with a diesel generator (GMG) serving as a backup. Computational simulations were conducted to assess system performance under increasing load demands, ranging from 10% to 50%. The results demonstrated consistent and satisfactory operation, with the diesel generator contributing less than 15% of the total energy output even at peak demand—highlighting the system’s efficiency and reduced reliance on fossil fuels.

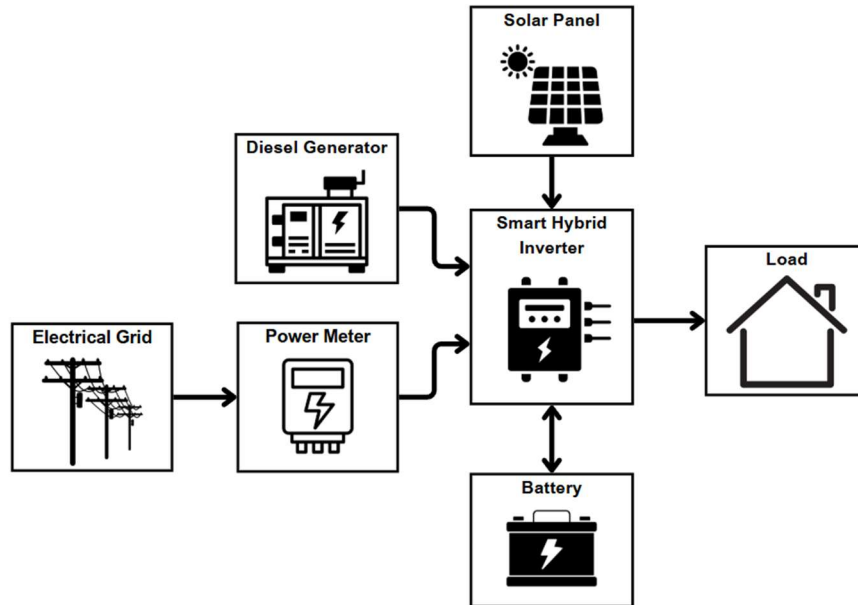


Figure 3. Hybrid electrical generation.

In most hybrid configurations, batteries and diesel generators are deployed as backup elements to ensure energy continuity, particularly in regions where the power supply from distribution networks is unreliable. In this context, Chedid and Sawwas (Chedid and Sawwas 2021) conducted a case study at the American University of Beirut to evaluate the implementation of a hybrid system composed of photovoltaic panels, battery storage, and a diesel generator. The findings revealed a significant reduction in both operational costs and energy dependence, affirming the technical and economic viability of hybrid photovoltaic systems.

2.5 Financial indicators

Financial indicators play a fundamental role in assessing the economic feasibility of investment projects, particularly in the context of energy systems (Pask et al. 2017). They provide quantitative tools to support decision-making by measuring profitability, risk, and return over time. Among the most widely used indicators in financial analysis are the Net Present Value (NPV), Internal Rate of Return (IRR), Discounted Payback Period, and the Levelized Cost of Energy (LCOE). These metrics allow for a comprehensive evaluation of costs and benefits throughout the lifecycle of a project, enabling comparisons between different investment alternatives under various economic conditions.

The Net Present Value (NPV), as defined by Samanez (Samanez 2010), represents the calculation—expressed in present value terms—of the future contributions outlined in the cash flow associated with an investment. This metric measures the present value of a project's cash flows over its useful life. The NPV is expressed mathematically in Equation 1.

$$NPV = -I + \sum_{t=1}^n \frac{CF_t}{(1 + K)^t} \quad (1)$$

Where: NPV: Net Present Value; I: Initial Investment; CF_t : Cash Flow at period “t”; K : Discount rate; t : Current Period.

The Internal Rate of Return (IRR) determines the rate of return that summarizes the profitability of a project. In this calculation, any external discount rates are excluded, relying solely on the project’s cash flow, as presented by Rigo and Cherobim (Cherobim et al. 2015). Mathematically, it is defined as the discount rate that results in a zero NPV, as given by Equation 1. As a decision-making criterion, if the internal rate of return “i” exceeds the discount rate “K”, the project is considered economically viable (Samanez 2010). The IRR is mathematically expressed in Equation 2.

$$0 = -I + \sum_{t=1}^n \frac{CF_t}{(1 + IRR)^t} \quad (2)$$

Where: IRR: Internal Rate of Return.

To determine the investment recovery period, the Discounted Payback Period is used. This method compares the present values of the cash flows to the initial investment. The point at which the cumulative present value of the cash flows equals the initial investment defines the discounted payback period of the project (Samanez 2010). Mathematical formulation is provided in Equation 3.

$$I = \sum_{t=1}^T \frac{CF_t}{(1 + K)^t} \quad (3)$$

Where: T: Discounted Payback.

The Levelized Cost of Energy (LCOE) represents the total cost associated with the energy generated by the system. It is calculated as shown in Equation 4.

$$LCOE = \frac{CAPEX + OPEX}{Eg} \quad (4)$$

Where: LCOE: Levelized Cost of Energy (BRL/kWh); CAPEX: Capital Expenditure (BRL); OPEX: Operational Expenditure (BRL); Eg: Total energy generated over the system's lifetime (kWh).

3 Methodology

To investigate the feasibility of alternative energy supply systems and assess their technical and economic implications, this study adopts a qualitative research approach. Due to the multidimensional nature of the technologies under analysis—ranging from power generation and storage to economic modeling—a case study strategy was chosen. This approach enables an in-depth and contextualized examination of a real-world scenario, providing empirical evidence grounded in actual operational conditions.

The methodological flow adopted in this work is outlined in Figure 4, which presents the sequential stages of the study, from theoretical framework definition to scenario analysis. This structured approach ensures the logical progression and integration of both technical data and contextual insights.

The initial phase of the research consisted of defining the conceptual and theoretical foundations that support the study. A comprehensive literature review was conducted to map existing knowledge on topics such as power interruptions, diesel generator sets (GMGs), off-grid photovoltaic (PV) systems, and battery storage technologies. This review helped contextualize the problem, establish the scope of the study, and identify the technological alternatives available for energy supply in rural and vulnerable areas.

Following the theoretical grounding, a specific case was selected based on its relevance and alignment with the study’s objectives. The chosen facility has a documented history of frequent power outages and utilizes a GMG for energy backup. Historical operational data were collected, including information on blackout frequency and duration, generator usage patterns, and financial losses associated with energy disruptions. The case was chosen using a targeted sampling approach, considering its alignment with the study’s focus, aiming to highlight the impacts of energy unreliability and the potential benefits of hybrid energy solutions.

Data collection encompassed both operational and environmental parameters. An operational survey of the facility was conducted to identify the types of electrical loads and their consumption profiles throughout a typical day. This information served as the basis for sizing the components of the proposed energy systems. Concurrently, solar resource availability was assessed through irradiance measurements, which quantify the solar energy incident per unit area (W/m^2) and are later integrated over time to determine solar irradiation (Wh/m^2), essential for PV system design.

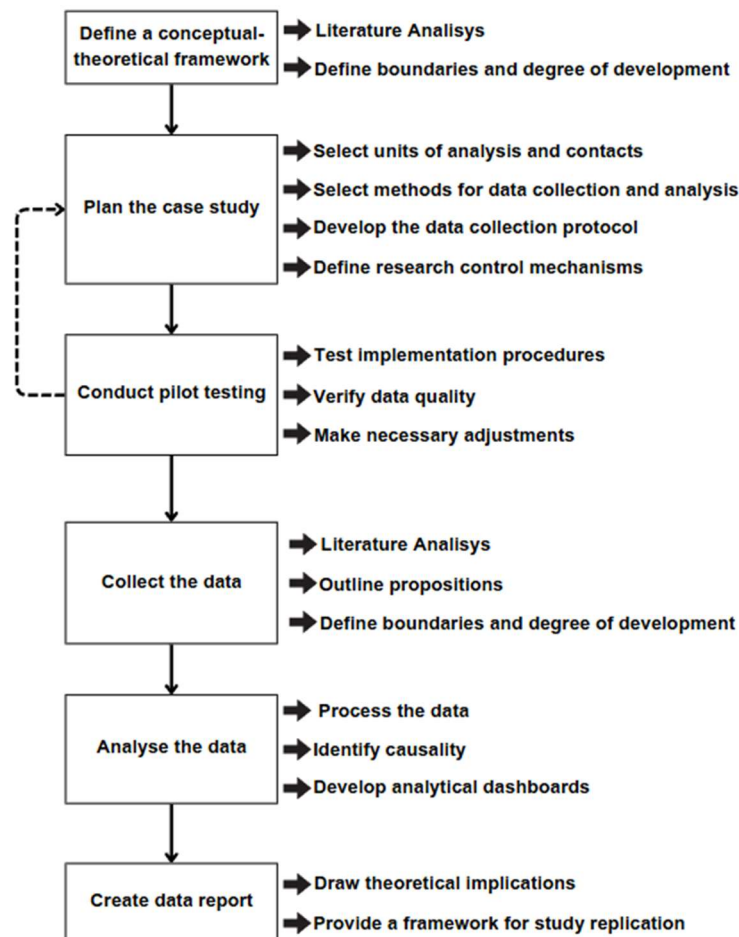


Figure 4. Diagram of the methodological steps adopted in the case study.

Based on the case characteristics and collected data, three alternative energy supply scenarios were modeled for comparative analysis:

- Grid + Diesel Generator (Grid + GMG);
- Grid + Off-grid Photovoltaic System + Diesel Generator (Grid + PV + GMG);
- Grid + Off-grid Photovoltaic System + Battery Storage (Grid + PV + Battery).

Each scenario was evaluated according to its technical performance and economic viability. Key indicators included the system's ability to meet demand, reduce dependence on fossil fuels, and mitigate losses caused by power outages—such as product spoilage, operational downtime, and livestock mortality. The total cost of ownership (TCO) for each configuration was calculated and compared, enabling the identification of the most appropriate solution in terms of reliability, sustainability, and cost-effectiveness.

4 Results

By analyzing the technologies currently available on the market, it is possible to identify the key equipment and configurations to be adopted. A case study was conducted on a rural property that experiences frequent power outages caused by the utility provider, resulting in significant financial losses for the owner. Relevant data were collected to guide the sizing of the available technologies and to perform a technical and economic analysis of the three proposed scenarios.

The facility under study consists of a dairy milking operation and a residential unit, both connected to a single-phase, three-wire metering center (two phases + neutral). The system includes a dedicated 10 kVA single-phase transformer delivering 220V/440V at the secondary, with protection provided by a 32 A double-pole circuit breaker. The load curve for the dairy was developed through an analysis of the facility's load schedule and the operating time of each piece of equipment. The detailed load schedule is included in Appendix A as the load curve is shown in Figure 5.

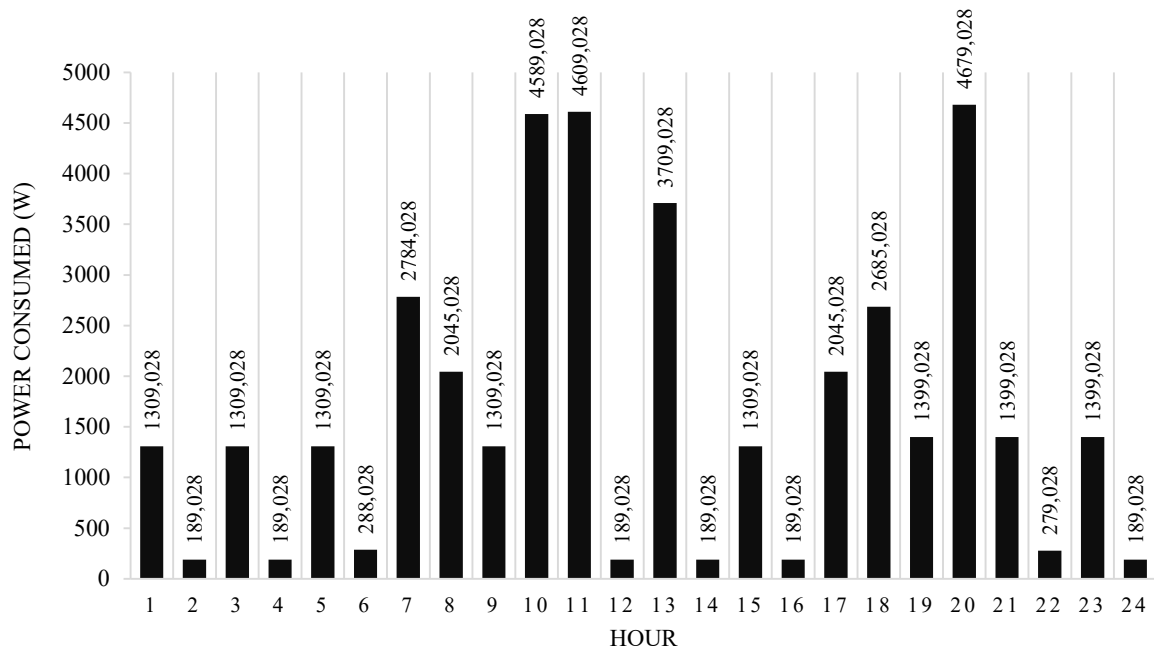


Figure 5. Load curve of the rural property.

Data on energy quality were collected, focusing on the main continuity parameters. The location experiences frequent power outages, with values exceeding state averages and those acceptable by local regulatory agency (ANEEL). The property owner reported an average of three outages per week, predominantly occurring in the early evening. The average duration of each outage is 12 hours, with normal service restored after this period. A key parameter for battery bank sizing is the average time between interruptions, which is 2 days. These energy quality parameters are summarized in Table 1.

Table 1. Interruption data of the rural property.

Data Collected	Value
Average duration of interruptions (hours)	12
Average weekly frequency of interruptions (days)	3
Average period between two interruptions (days)	2

4.1 Current scenario of the facility

The facility's primary source of income is the sale of stored milk to a distributor, a process directly dependent on power reliability. During power outages, the price per liter of milk drops from R\$3.50 to R\$3.00, resulting in a 25% loss in revenue, as any milk not sold and collected by the distributor must ultimately be discarded.

Therefore, the costs and financial losses related to milk sales in the current scenario are outlined in Table 2. Daily energy costs include energy consumption on both days with and without power interruptions, as well as the corresponding electricity tariff of 0.77 BRL/kWh, as detailed in Table 3.

Table 2. Milk Price and Loss Comparison.

	Price of milk per liter (BRL)	Price of 500L milk tank (BRL)	Revenue Loss (BRL)
Without interruption	3.50	1750.00	0
With interruption	3.00	1500.00	250.00

Table 3. Daily Electricity Consumption and Cost Comparison.

	Daily electricity consumption (kWh)	Daily electricity cost (BRL)
Without interruption	35.74	27.52
With interruption	21.88	16.85

To determine the facility's total annual cost, energy consumption costs on days with and without interruptions were added to the revenue losses due to milk price reductions. The resulting total annual cost is presented in Table 4.

Table 4. Annual Operational Costs with and without Power Interruptions.

Costs	Days	Total Cost (BRL)
Electricity cost Without interruption	17	467.82
Electricity cost with interruption	13	219.05
Loss related to milk sales	13	3,250.00
Monthly total cost	30	3,936.87
Annual total cost	365	47,242.42

4.2 Analysis Of Grid + Diesel Generator (Grid + GMG)

In this configuration, the diesel generator (GMG) serves as a backup power source during outages, operating for 12 hours per interruption (from 7:00 PM to 6:59 AM).

After identifying the key costs associated with this scenario, a financial projection was conducted over a 30-year time horizon. The configuration requires an initial investment of R\$11,819.94 and generates an annual negative cash flow of R\$29,752.40. The generator must be replaced every 11 years. This negative cash flow reflects the system's operating expenses, including grid electricity costs, diesel fuel consumption, and maintenance.

4.3 Analysis Of Grid + Off-Grid Photovoltaic System + Diesel Generator (Grid + PV + GMG)

This scenario incorporates an off-grid photovoltaic (PV) system to supply electricity during daylight hours, while the diesel generator (GMG) provides backup power during nighttime outages. The configuration demands an initial investment of R\$67,960.12 and leads to an annual negative cash flow of R\$25,050.21. The GMG must be replaced every 11 years, and the inverters every 10 years.

As in the previous scenario, the negative cash flow is primarily due to operational expenses, including grid electricity consumption, diesel fuel for the GMG, and system maintenance.

4.4 Analysis Of Grid + Off-Grid Photovoltaic System + Batteries (Grid + PV + Battery)

This scenario functions similarly to the previous one, but battery banks are used as the backup energy source during power outages instead of a diesel generator. The initial capital expenditure (CAPEX) required for this configuration is R\$106,578.00, with a first-year negative cash flow of R\$3,540.23. Inverters must be replaced every 10 years.

Unlike the previous scenarios, the negative cash flow in this case reflects only operational expenditures (OPEX), limited to grid electricity consumption and system maintenance—excluding any fuel or generator-related costs.

4.5 Comparative analysis

The main cost components of the three scenarios are presented in Table 5.

Table 5. Detailed installation and operating cost of the three analyzed systems.

	Capex		
	RE+GMG	RE+PV+ GMG	RE+PV+BATT
Price of GMG Acquisition	11,819.94 BRL	11,819.94 BRL	-
Price of off-grid PV Acquisition	-	50,000.18 BRL	50,000.18 BRL
Price of off-grid PV Installation	-	6,140.00 BRL	6,140.00 BRL
Price of Battery Acquisition	-	-	50,437.82 BRL
	Opex		
Grid Electricity cost early	8,242.42 BRL	-	-
GMG Electricity cost early	19,509.98 BRL	-	-
Preventive Maintenance	2,000.00 BRL	2,000.00 BRL	-
Annual Operating Hours – GMG	1872 Hours	1872 Hours	-

Cost of GMG substitution (11 Years)	11,819.94 BRL	11,819.94 BRL	-
Off-grid system maintenance	-	637.50 BRL	637.50 BRL
Cost of inverter substitution (10 Years)	-	7,346.07 BRL	7,346.07 BRL

Investment returns are illustrated through comparative cash flow graphs for each scenario, shown in Figure 6 (a), (b), and (c).

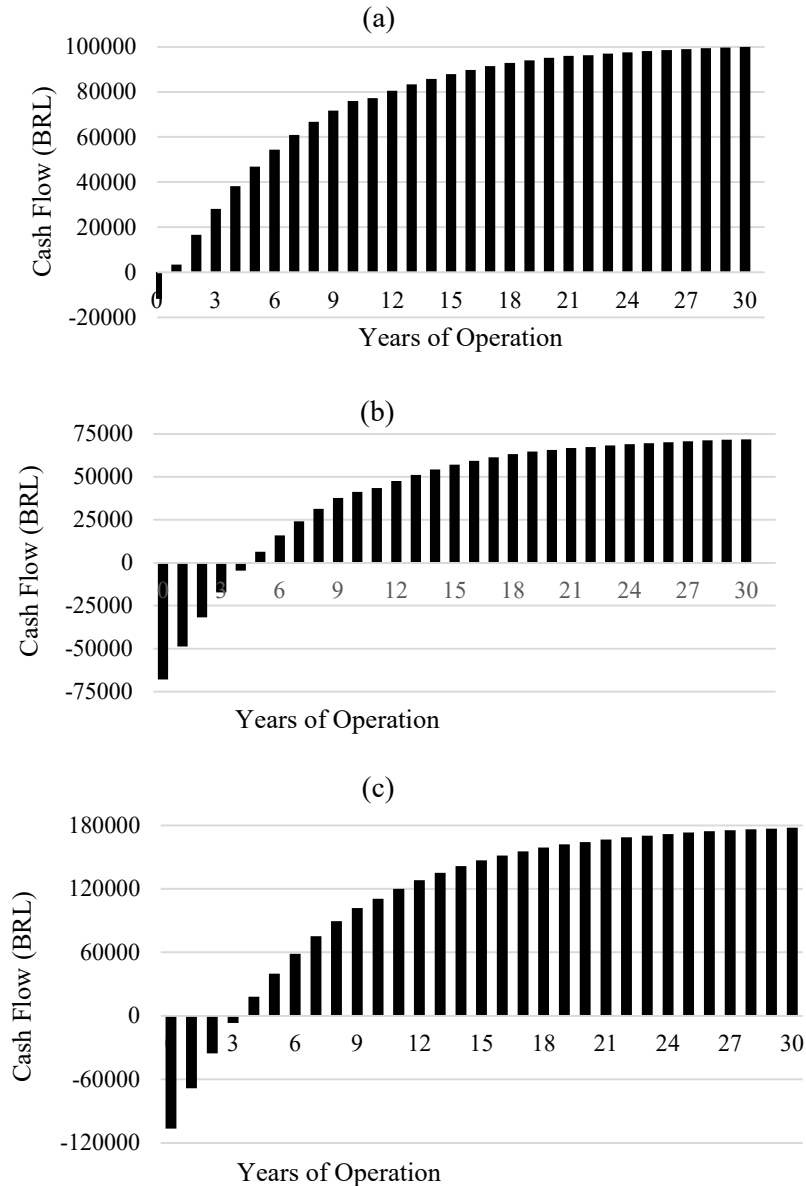


Figure 6. Comparative cash flow for the different scenarios (a) RE+GMG (b) RE+PV+GMG (c) RE+PV+BATT.

The key financial indicators analyzed in this study are presented in Table 6.

Table 6. Key financial indicators for each scenario over 30 years.

	NVP (BRL)	Discounted payback (Years)	LCOE (BRL/kWh)
<i>RE+GMG</i>	-210,260.29	0.48	0.547
<i>RE+PV+GMG</i>	-238,379.30	4.43	0.593
<i>RE+PV+BAT</i>	-132,676.36	3.27	0.330

5 Conclusion

This study investigated the viability of off-grid alternative energy generation technologies available on the market, aiming to identify the most suitable solution for the current situation of a commercial dairy production and storage facility located in the municipality of Cezarina, in the state of Goiás, Brazil, which faces frequent and prolonged power supply interruptions.

Adopting a case study methodology, the facility's technical, financial, and operational characteristics were assessed. Based on the data collected, three potential solution scenarios were designed, incorporating different combinations of alternative energy sources: a diesel generator (GMG), an off-grid photovoltaic (PV) system, and battery storage. The configurations evaluated were: Grid + GMG (RE+GMG), Grid + Off-grid PV + GMG (RE+PV+GMG), and Grid + Off-grid PV + Battery (RE+PV+Battery).

Each scenario was technically sized using commercially available technologies, and key financial components were estimated, including capital expenditure (CAPEX), operational expenditure (OPEX), and scheduled equipment replacements over a 30-year analysis horizon—aligned with the average production warranty offered by PV module manufacturers.

Among the alternatives, the RE+PV+Battery scenario required the highest initial investment, while the RE+GMG scenario had the lowest CAPEX, nearly nine times smaller. However, in terms of operational costs, the battery-based solution proved more economical, as it benefits from daytime energy generation via the off-grid PV system and incurs no fuel-related expenses during outages.

Financial analysis revealed that the RE+PV+Battery scenario resulted in the lowest Net Present Value (NPV), at -R\$132,676.36, indicating a greater long-term financial burden compared to the other options. Nevertheless, when comparing the projected cash flows of each configuration with the current operating conditions, the discounted payback period showed that the RE+GMG scenario achieved the quickest return on investment, with a payback time of just 0.48 years.

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Appendix A: Load Schedule of the dairy

Load Schedule																											
Loads	Unit Power (W)	Qtd.	Total Power (W)	Operating hours																							
				0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
Submersible Pump	320	2	640							1											1						
Grinder 7,5CV 220/440	5500	1	5500										0.5														
Electric Fence	15	1	15	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Milk Cooling Tank 500L	1120.0	1	1120.0	1		1		1		1	1	1		1		1		1		1	1	1		1		1	
Refrigerator	70.8	1	70.8	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Freezer 420 L	103.2	1	103.2	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
Automatic Milking System	736	1	736							1	1									1	1						
Milking Area Lighting	9	1	9						1	1																	
House Lighting	9	10	90						1	1												1	1	1	1	1	
Washing Machine	550	1	550										1														
Electric Shower	4400	2	8800										0.5										0.5				
Electric Oven	2400	1	2400													1											
TOTAL	15233.03	23	20034.03	4	3	4	3	4	5	8	5	4	3.5	5.5	3	5	3	4	3	5	6	5	4.5	5	4	5	3
Total Energy consumed per hour (W/h)				1309.03	189.03	1309.03	189.03	1309.03	288.03	2784.03	2045.03	1309.03	4589.03	4609.03	189.03	3709.03	189.03	1309.03	189.03	2045.03	2685.03	1399.03	4679.03	1399.03	279.03	1399.03	189.03