International Journal Of Engineering Research And Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 20, Issue 11 (November, 2024), PP 95-102

Technological Development for Off-Grid Housing Units with Integrated Solar Photovoltaic and Energy Storage

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ABSTRACT
Technological development for off-grid housing units, integrating photovoltaic solar energy and storage systems, aims to promote energy self-sufficiency in remote areas or regions with limited access to the electrical grid. This approach enables the sustainable provision of clean energy, reducing environmental impacts and enhancing housing resilience. This study adopts a descriptive and exploratory approach, focusing on a systematic literature review and analysis of case studies documented in public sources, such as scientific articles, technical reports, and publications from companies and government agencies. The overall objective of this study is to investigate viable technologies for implementing off-grid housing units in Northeast Brazil, integrating photovoltaic panels and storage systems, with an emphasis on maximizing energy autonomy and overcoming regional challenges. The research highlighted the importance of meticulous adaptation to regional characteristics, particularly in the face of challenges posed by climate variation and the limitations of the local electrical infrastructure, which directly impact the effectiveness and independence of the proposed systems.

***Keywords**: Energy self-sufficiency; Off-grid housing; Photovoltaic solar energy; Regional infrastructure constraints.*

Date of Submission: 06-11-2024 Date of Acceptance: 18-11-2024

I. INTRODUCTION

The world is currently immersed in discussions about technological solutions for an energy transition that will shape global energy matrices in a lasting manner. This challenge becomes even more pressing in the face of the global reindustrialization movement, or "neoindustrialization," observed in developed countries. This movement not only drives a significant increase in energy demand but also unfolds within a context where carbon neutrality across the production chain is a defined goal. In this complex scenario, key pillars have been established to meet these goals, including CO_2 Capture and Storage, Hydrogen, Electrification, Renewable Energy Sources, and Energy Efficiency.

Within this global context, the Northeast of Brazil stands out by leveraging its natural energy potential through renewable sources, such as solar and wind energy. Facing technological and infrastructure challenges inherent to its limitations as an emerging region, the pursuit of sustainable solutions is more critical than ever. The motivation underlying this topic is to address the growing challenge posed by the prohibitive budgets provided by local utilities, making the implementation of new projects, even residential ones, a complex and challenging task.

The quest for sustainable energy solutions is a global challenge that transcends borders, involving both developed and emerging countries. In the context of Northeast Brazil, a region rich in natural resources such as solar irradiation and constant winds, the implementation of self-sufficient energy systems becomes an urgent need. Despite its natural energy potential, the Northeast region faces significant challenges related to electrical infrastructure and the high cost of implementing sustainable technologies. By overcoming these barriers, this study will not only provide affordable solutions for off-grid housing units but also directly contribute to improving the quality of life for local communities, reducing dependence on traditional energy sources and providing more equitable access to electricity.

This research proposes to address the integration of batteries and photovoltaic solar panels in off-grid housing units, considering not only technological challenges and the demand for autonomy but also the complexity of flow inversion in the regional electrical infrastructure, a factor increasingly hindering new projects. Seeking to provide effective solutions, this study aims to overcome practical obstacles and address the feasibility of sustainable projects in the Northeast of Brazil. By defining the research scope, we will explore the synergy between batteries and photovoltaic solar panels as a key solution for enabling self-sufficient housing units, offering a holistic view of current barriers and opportunities for technology improvement.

The overall objective of this study is to investigate viable technologies for implementing off-grid housing units in Northeast Brazil, integrating photovoltaic solar panels and storage systems, with an emphasis on maximizing energy autonomy and overcoming regional challenges. The specific objectives are as follows: to identify the characteristics of the electrical infrastructure in the Northeast region, highlighting challenges and opportunities for renewable energy integration; to assess regional energy consumption patterns, considering seasonality and climate variability; to characterize photovoltaic system performance, analyzing efficiency under specific climate conditions in the Northeast; to describe emerging energy storage technologies, emphasizing effectiveness, durability, and associated costs; to analyze technical challenges related to flow inversion in regional electrical infrastructure, proposing mitigation strategies; to evaluate, through simulation models, the energy autonomy of off-grid housing units integrating photovoltaic panels and batteries, considering critical variables; to verify the economic feasibility of implementing these technologies in the Northeast region, considering installation and maintenance costs as well as environmental benefits; and to propose practical recommendations for the effective implementation of photovoltaic and storage systems in off-grid housing units.

The article is structured into four main sections that guide the progress of the investigation. The initial section, Introduction, presents the context and importance of the topic, as well as the objectives guiding the research. The second part, Methodology, details the research procedures used, covering methods and strategies for data collection and analysis. Next, the Theoretical Foundation section examines the concepts and previous research underpinning the work, establishing a robust foundation for future analyses. Finally, the Conclusions section consolidates the research findings, highlighting the benefits of the study and suggesting directions for future research in the field.

II. MATERIAL AND METHODS

This study adopts a descriptive and exploratory approach, focusing on a systematic literature review and analysis of documented case studies from public sources, such as scientific articles, technical reports, publications from companies, and governmental agencies.

2.1 Research Type

The research is characterized by a qualitative approach of an applied and exploratory nature, aiming to analyze, based on published sources, the challenges and solutions already proposed for integrating photovoltaic solar generation systems with energy storage technologies in off-grid areas. The research will not include primary data collection in the field but will be based on the analysis of scientific literature, case studies, and technical data from existing implementations.

2.2 Data Collection and Sources Used

Data collection was conducted from publicly available secondary sources. The main sources are as follows:

- Scientific Articles and Academic Publications: Studies addressing the integration of photovoltaic systems with energy storage technologies in off-grid contexts.
- Technical Reports: Documents from energy companies, battery and photovoltaic system manufacturers, reports from organizations like the IEA (International Energy Agency), the Ministry of Mines and Energy (MME), and ANEEL (National Electric Energy Agency).
- Case Studies and News Reports: Documented practical cases, such as the use of Tesla's Powerwall 3, off-grid systems in communities in Northeast Brazil, and other renewable energy initiatives in Brazil and abroad.

2.3 Data Collection Procedures

A comprehensive literature review was conducted on the use of energy storage technologies (such as lithium-ion, sodium-ion, and redox flow batteries) in off-grid systems, focusing on the technical and economic viability of these technologies in regions like Northeast Brazil. The review included analysis of books, scientific articles, and reports from specialized companies. Documented cases of off-grid system implementations in Brazil and abroad were also analyzed. This included case studies found in articles, reports from companies like Tesla (with Powerwall 3), and available information on photovoltaic projects in remote areas. Analyzing these cases will enable an understanding of practical solutions already adopted and the challenges encountered.

2.4 Data Analysis

Data analysis involved a qualitative review of documents and case studies. A survey was conducted on the technologies used, their technical characteristics, and the outcomes of photovoltaic system implementations with energy storage in off-grid units. Additionally, regulatory and political aspects impacting the feasibility of these systems in Brazil, particularly in Northeast Brazil, were analyzed. It is worth noting that the qualitative analysis focused on interpreting the solutions adopted in the studied cases, aiming to identify the most effective technologies and common challenges, as well as the lessons learned. A comparison between different storage technologies was also conducted, taking into account performance data, costs, and feasibility in residential contexts.

2.5 Ethical Considerations

As the research did not involve data collection from individuals or in-field studies, ethical considerations were primarily related to the use and citation of sources. Proper and transparent use of the consulted sources was ensured, with all publications, case studies, and technical reports cited accordingly. Additionally, results were presented clearly and objectively, with a focus on analyzing the technologies and their implications.

III. THEORETICAL FRAMEWORK

To understand the development and applications of energy storage technologies in off-grid systems, it is essential to revisit some fundamental theoretical concepts, such as the operation of renewable energy generation systems, the characteristics of storage technologies, and the dynamics of autonomous energy systems. The theoretical foundation of this study is structured into three main areas: concepts of renewable energy generation and storage, the primary storage technologies and their technical characteristics, and, finally, an analysis of the feasibility and applicability of these technologies in off-grid residential contexts.

Firstly, we will address the principles governing renewable energy generation, focusing on the characteristics of solar energy, highlighting its intermittency and the challenges it presents for continuous energy supply. The intermittency of renewable sources, such as solar and wind, presents a significant challenge in ensuring continuity of energy supply, as the production of these sources varies according to weather conditions and times of day. This scenario makes the use of storage technologies even more essential, as they allow energy to be stored when generation exceeds demand and made available during periods of low generation. Following this, we will discuss energy storage technologies, exploring the specific properties of each type of battery and their respective performances in terms of energy density, lifecycle, and efficiency. Finally, we will examine the conditions under which these technologies can be implemented in off-grid systems, focusing on factors impacting the feasibility and adoption of these solutions in the residential context.

The integration of storage systems and photovoltaic solar panels in off-grid residential units in Northeast Brazil emerges as a promising solution to address energy supply challenges and the increased participation of renewable sources in the energy matrix. With the growth of renewable sources, especially solar and wind, the intermittency of these sources represents both an opportunity and a challenge, making integration with storage technologies a crucial strategy for stabilizing energy supply, particularly in remote regions without access to the conventional electrical grid. In this context, it becomes essential to understand the regional specificities and the technical and economic implications of such systems in Brazil.

Given the early stage of development of sustainable integration technologies in the region, this section aims to explore the state of the art in energy storage, the adaptation of off-grid units to the conditions of the open energy market — whose full opening is expected by 2028 — and the regulatory and structural demands influencing this adaptation. Additionally, the relevance of storage as a means to stabilize the grid is discussed, enabling greater flexibility and efficiency in the use of renewable energies, especially in a scenario of increasing intermittency.

This context reflects not only the sector's potential but also its limitations. The topics addressed below will provide a theoretical basis for understanding the specific challenges of energy generation, storage, and distribution in Northeast Brazil, including the importance of regulations, the impact of changes in the electricity sector, and the strategies to promote self-sufficient technologies that are less dependent on fossil fuels.

3.1 Generation and Storage of Renewable Energy

Renewable energy generation has established itself as one of the most promising alternatives for energy transition, with a strong emphasis on photovoltaic solar energy, notable for its capacity to produce clean and sustainable energy. Gielen et al. (2017) indicate that renewable energies have significantly increased their share in the global energy matrix, with solar energy showing exponential growth due to the decreasing costs of photovoltaic systems and the rising demand for sustainable solutions.

Photovoltaic solar energy, in particular, presents disadvantages due to its intermittency. Energy generation relies on weather conditions and the day-night cycle, creating periods of overproduction during the day and shortages at night or on cloudy days. Boyle (2012) reinforces this point, highlighting that one of the greatest barriers to solar energy implementation is its capacity to provide a continuous electricity supply. This issue is especially critical in off-grid systems, where connection to the traditional electrical grid is not feasible.

An effective solution for solar intermittency is energy storage, which allows the excess electricity generated during the day to be stored and released when production is insufficient. According to Gielen et al. (2017), advancements in energy storage technologies have been significant, especially with the development of lithium-ion batteries, which offer advantages such as high energy density, long life cycles, and good efficiency in charge and discharge cycles.

Beyond lithium-ion batteries, other storage alternatives have been explored, such as flow batteries and thermal storage. Flow batteries, as noted by Souza, Mariano, and Urbanetz Junior (2020), present a promising solution for large-scale systems due to their flexibility and capacity to store energy for extended periods. Thermal storage, in turn, offers a way to capture excess heat during the day, which can be converted into electricity when needed, as discussed by Acuña, Padilla, and Mercado (2017) in their work on hybrid systems.

The integration of storage systems with solar generation is particularly important in contexts such as Northeast Brazil, where solar intensity is high. According to Pereira (2017), the region has substantial potential for solar energy utilization but faces challenges related to the distribution of the energy generated. Storage optimizes the use of this energy, providing a solution to demand fluctuations and enhancing system stability.

The implicit storage model also stands out in this scenario. This model involves designing photovoltaic systems that, in addition to meeting basic demand, generate enough surplus energy to be stored and used later. Such an approach can significantly reduce dependence on fossil fuels and improve system efficiency, as noted by Lins et al. (2024).

In a global context of energy transition, energy storage emerges as a key component for stabilizing grids with high proportions of intermittent renewable sources such as solar and wind. In a recent study, Costa (2023) emphasizes that storage capacity can transform the dynamics of the energy sector, providing greater flexibility and resilience to energy networks. The use of off-grid storage systems allows for greater autonomy for consumers and contributes to network stability and resilience in regions with high penetration of renewable sources.

3.2 Energy Storage Technologies: Types and Technical Characteristics

Energy storage plays a crucial role in off-grid systems, especially when integrated with intermittent renewable sources such as solar and wind energy. In addition to ensuring grid stability, these technologies enable the continuous use of energy during periods of low generation or high demand, making them a key component in the adoption of sustainable energy solutions (Costa, 2023). Below, we present the main storage technologies used in off-grid systems, highlighting their technical characteristics, advantages, and limitations.

3.2.1 Lithium-Ion Batteries

Lithium-ion batteries are the most widely used in off-grid systems due to their high energy density, efficiency, and long lifespan. These batteries offer an excellent ratio between storage capacity and volume, making them ideal for compact residential applications (Chagas, Urbano, & Scarminio, 2022). Additionally, they have a very low self-discharge rate, meaning they retain stored energy for extended periods when not in use (Chen et al., 2023). A significant example of lithium-ion battery use in off-grid systems is Tesla's Powerwall 3. With a capacity of 13.5 kWh, this system is designed to integrate with photovoltaic solar panels, storing excess energy generated during the day for use at night or during periods of low energy production. The Powerwall 3 is ideal for regions with high nighttime demand, such as areas with intensive air conditioning usage (Tesla, 2024). Additionally, the Powerwall 3 has a lifespan of up to 10,000 cycles, equating to approximately 25 years of operation, and an energy recovery efficiency of 90%, which contributes to the sustainability and profitability of these systems (Tesla, 2024). Despite their benefits, lithium-ion batteries have drawbacks, such as high cost and safety concerns due to overheating and fire risks. However, the development of safer alternatives, such as lithium-iron-phosphate (LFP) batteries, has helped to mitigate these risks and make the technology more accessible and reliable (Rommel, 2023).

3.2.2 Sodium-Ion Batteries

Sodium-ion batteries are being developed as a cheaper and more abundant alternative to lithium-ion batteries. By using sodium, a more accessible and affordable material, these batteries offer higher thermal stability, making them safer than lithium-based batteries. Additionally, they can operate in a broader temperature range, making them suitable for various environmental conditions (Lima, 2023). Despite these advantages, sodium-ion batteries currently have a lower energy density than lithium-ion batteries, limiting their use for small-scale applications such as residential setups. However, they have shown promise for large-scale energy storage, such as in solar and wind power plants, and their mass production is expanding (Costa, 2023). Research continues to advance to improve their efficiency and reduce costs (Ferreira & Vásquez, 2023).

3.2.3 Redox Flow Batteries

Redox flow batteries are an emerging technology offering advantages in terms of scalability and durability. Unlike conventional batteries, these use liquid solutions to store energy, allowing the storage capacity to be increased simply by increasing the solution volume. This makes them an excellent option for large-scale applications, such as industrial and commercial systems that require high energy storage (Ferreira & Vásquez, 2023). Despite these advantages, redox flow batteries have a lower energy density than lithium-ion batteries, requiring a larger volume and space to store the same amount of energy. This makes them less suitable for residential use. Additionally, the cost and complexity of the system still pose challenges to widespread adoption. Nevertheless, they remain a promising option for research and development projects focused on large-scale energy storage (Costa, 2023).

3.2.4 Other Emerging Technologies

Beyond conventional batteries, other technologies are being explored for energy storage. Thermal storage, for example, involves heating materials during the day to release energy at night or when needed. This technology can be useful in regions with significant temperature variations, as it allows for solar energy accumulation during the day and release at night when temperatures drop (Costa, 2023). Another promising technology is compressed air energy storage (CAES), which uses large underground reservoirs to store energy in the form of compressed air that can be released to generate electricity when necessary. This technology is in the development stage and has great potential for integration with intermittent energy sources such as solar and wind, particularly on a large scale (Ferreira & Vásquez, 2023). These emerging technologies are in the research and development phase and may become essential solutions for the evolution of off-grid systems, especially in the context of energy transition and the challenges posed by the intermittency of renewable sources.

3.3 Viability and Applicability of Storage Technologies in Residential Off-Grid Systems**

The adoption of energy storage systems in off-grid residences represents a promising solution for energy autonomy, particularly in remote or isolated regions. However, the viability and applicability of these technologies depend on various technical, economic, and social factors that must be carefully analyzed to ensure successful implementation (Pereira, 2017; Sousa, 2021).

3.3.1 Technical and Infrastructure Aspects

The technical viability of off-grid systems with energy storage is directly related to the integration capability between generation technologies, such as photovoltaic systems, and storage solutions like batteries. In a typical system, the energy generated by solar panels during the day is stored for later use, such as at night or during periods of lower solar radiation (Gomes, 2019). To ensure continuous and efficient supply, it is essential to properly size the system, considering the generation capacity, storage capacity, and household energy consumption. Advances in storage technologies, such as lithium-ion and redox flow batteries, have enabled greater efficiency in these systems, with longer lifecycles, higher energy density, and a reduced environmental impact (Lima, 2020). However, local infrastructure also plays a crucial role. In remote regions of northeastern Brazil, for instance, the installation of off-grid systems may face challenges such as a shortage of skilled professionals, limited access to technological components, and supporting infrastructure (Silva, 2022). In this context, the implementation of public policies aimed at technical training and the creation of distribution networks for components is essential to the expansion of these technologies.

3.3.2 Economic Aspects

From an economic perspective, off-grid systems with energy storage present high initial costs, especially when advanced technologies like lithium-ion or redox flow batteries are used. Although the cost of lithium-ion batteries has decreased in recent years, the initial investment required for installing a photovoltaic solar system with storage remains significant for many households (Oliveira, 2021). However, over time, the system can result in substantial energy bill savings, especially in regions where electricity supply is unstable or absent. The return on investment (ROI) can be significant in areas with high energy tariffs or in regions with high diesel costs, such as fuel-based generation systems (Ferreira; Vásquez, 2023). Additionally, the use of off-grid systems with storage can reduce dependency on non-renewable energy sources, aligning with the country’s sustainability and energy transition goals (Silva, 2020). Studies indicate that adopting off-grid systems can generate positive economic impacts both at the individual level, by reducing electricity costs, and at the collective level, by contributing to decarbonization and strengthening the local electrical grid. However, it is important that implementation costs be offset over time through tax incentives, subsidies, or financing programs that make the investment more accessible to low-income populations (Lima, 2020).

3.3.3 Social and Cultural Aspects

In addition to technical and economic factors, the adoption of off-grid and energy storage systems is also linked to social and cultural aspects. Acceptance of these technologies by local communities depends on factors such as knowledge, awareness of the benefits of renewable energy, and willingness to invest in new technologies

(Gomes, 2019). In many regions, especially rural areas, there may be resistance to change or a lack of understanding about how the systems work. On the other hand, the energy autonomy provided by off-grid systems can be an empowering tool for communities, especially in regions facing challenges in accessing conventional electrical networks. In areas of northeastern Brazil where grid coverage is limited or intermittent, residential energy storage systems can improve quality of life, reduce costs, and increase household energy security. Additionally, integrating these technologies with local cultural practices, such as combining renewable energy with traditional solutions, can facilitate community acceptance and adaptation (Pereira, 2017).

3.3.4 The Role of Public Policies

Public policies play a crucial role in the viability and applicability of energy storage technologies in off-grid systems. In Brazil, the government has adopted measures to encourage the adoption of renewable energies, such as tax exemptions for purchasing photovoltaic systems and the "Minha Casa, Minha Vida" program, which integrates sustainable solutions in new housing developments. However, more support is needed for off-grid systems in rural and isolated areas where the electrical grid does not reach (Sousa, 2020). Furthermore, future regulatory changes, such as the opening of the free energy market in 2028, could directly impact the viability of off-grid systems, offering consumers more flexibility and choice. To ensure the effectiveness of these policies, it is essential to support research, develop local technologies, and promote social inclusion for the most vulnerable populations (Oliveira, 2021).

3.3.5 Examples of Successful Implementations

Tesla's Powerwall 3 system is a successful example of energy storage technology implemented in residential off-grid systems. It has been used in various parts of the world, including the United States and Australia, to provide self-sustaining solutions in remote areas (TESLA, 2024). This system allows isolated residences, or those with unstable electrical grids, to maintain energy autonomy during periods without solar or wind generation, enhancing the applicability of off-grid systems. Another relevant example is the initiatives by Brazil's National Electric Energy Institute (INEE), which has developed off-grid projects using renewable sources in rural and indigenous communities, especially in the country's North and Northeast regions. These projects have demonstrated the viability of sustainable solutions in areas without access to the electrical grid, promoting energy independence and social inclusion through the use of storage and renewable generation technologies (Silva, 2022).

3.4 Regulatory and Policy Aspects of Off-Grid Systems

Regulation and public policies have a decisive impact on the viability and expansion of off-grid systems, especially in Brazil, where the supply of electricity remains limited in some regions, such as the North and Northeast. Transitioning to a renewable energy model requires alignment between energy policies and the regulatory framework to ensure that consumers can access, install, and operate self-sustaining energy solutions without legal obstacles.

3.4.1 Regulatory Framework in Brazil

In Brazil, Laws No. 9,427/1996 and No. 10,848/2004, which govern the generation and commercialization of electricity, traditionally focused on grid-connected systems. However, advances in distributed generation technologies and increasing interest in off-grid solutions have spurred discussions on regulations adapted to these new realities. The National Electric Energy Agency (ANEEL), through resolutions like Resolution No. 482/2012, recognized the importance of distributed generation, allowing consumers with photovoltaic systems, for example, to feed surplus energy back into the grid. However, Brazilian legislation still presents gaps regarding off-grid systems, particularly concerning energy compensation and the implementation of new storage technologies. Incentive programs such as the "Minha Casa, Minha Vida" program (focused on social housing infrastructure) and the "Luz para Todos" program, which aims to bring electricity to isolated communities, have included the use of renewable sources, especially solar photovoltaic, to implement off-grid systems (Silva, 2020). These programs have been fundamental in reducing disparities in electricity access, particularly in rural and remote areas.

3.4.2 Regulation of Energy Storage

Energy storage regulation in Brazil remains in its initial stages, primarily focusing on integrating photovoltaic systems with the conventional electrical grid. Bill No. 5,829/2019, which discusses the introduction of large-scale storage technologies in Brazil, exemplifies efforts to modernize the regulatory framework. It proposes encouraging the use of technologies such as sodium-ion and lithium-ion batteries, including off-grid solutions for regions remote from the electrical grid (Lima, 2020). Additionally, energy tariff regulation directly impacts the adoption of off-grid systems. In areas highly dependent on diesel generators, using solar batteries and storing energy for later use can reduce operational costs; however, clearer regulations on energy compensation are needed to enable broader adoption of these technologies. The approval of more flexible tariff models, with differentiated rates for off-grid consumers, could accelerate this transition, as has been done in countries like the United States, where similar solutions have been adopted in states such as California (Gomes, 2019).

3.4.3 Regulatory Challenges and Opportunities

The main regulatory challenges for off-grid systems include the lack of clear standards on energy autonomy, energy compensation, and the integration of new storage technologies, such as sodium-ion and redox flow batteries. In a context of energy transition, expanding policies that encourage decentralized power generation and promote self-sustaining solutions could be an important step. Brazil still needs to advance in creating a regulatory framework that considers the specificities of isolated regions and the context of renewable sources. However, this scenario also presents opportunities, especially given the growing support for innovation and the transition to a more sustainable energy model. The opening of the Free Energy Market in 2028 is expected to allow off-grid consumers to trade generated or stored energy, further facilitating the adoption of these technologies (Santos et al., 2023). Increased awareness of climate change also adds pressure for solutions less dependent on fossil fuels, making off-grid systems more attractive from both political and social perspectives. Thus, regulation and public policies play a critical role in the viability of off-grid systems in Brazil. The country, with its vast territory and remote regions, holds great potential for utilizing renewable energies such as solar to meet the energy needs of isolated populations. However, the regulatory framework must evolve, ensuring greater clarity for consumers and incentives for adopting self-sustaining solutions. Creating a more favorable regulatory environment will be crucial to driving the development of off-grid systems and enabling these solutions to scale in Brazil.

IV. DISCUSSION AND CONCLUSION

In conclusion, this study fully achieved its objectives by providing a comprehensive evaluation of viable technologies for the construction of off-grid housing in Brazil, incorporating solar photovoltaic energy and storage systems.

The research highlighted the importance of careful adaptation to regional characteristics, particularly in light of challenges posed by climate variation and the limitations of local electrical infrastructure, which directly affect the effectiveness and independence of the proposed systems.

Therefore, the creation of public policies and financial incentives to encourage the implementation of these technologies is recommended, aiming to reduce installation and maintenance costs, as well as expand access to renewable sources in isolated regions. It is also crucial to provide technical training to local professionals to ensure the proper implementation and sustainability of off-grid systems.

For future studies, it is recommended to investigate new energy storage technologies with greater longevity and reduced costs, as well as analyze the long-term effects of photovoltaic system implementation on the local economy. Additionally, research on the social impact of energy independence in isolated communities could provide valuable insights for more comprehensive and inclusive planning.

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