Journal of Renewable Engineering
E-ISSN : 3046-7624
https://nawalaeducation.com/index.php/JORE/index
Vol.2.No. 4 August 2025
DOI : https://doi.org/10.62872/ex26fj18

# Literature Review: Integration of Hybrid Renewable Energy Systems in Remote Areas

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Received: June 22, 2025
Revised : July 25, 2025
Accepted: August 02, 2025
Published: August 15, 2025

**ABSTRACT**

The availability of equitable and sustainable energy in remote areas is a major challenge for national development, primarily due to limited infrastructure and electricity access from conventional grids. Hybrid energy systems that combine renewable energy sources such as solar, wind, and microhydro with energy storage or diesel backup have emerged as an adaptive solution to address energy needs in off-grid areas. This study uses a qualitative approach based on literature to explore relevant hybrid energy system integration practices, challenges, and models across various geographic and social contexts. The study identifies that the success of hybrid system implementation is determined not only by its technological configuration but also by local social, economic, and institutional factors. Technological advances such as the Internet of Things (IoT) and smart energy management systems have contributed to improving system efficiency and reliability. However, obstacles remain in the form of limited funding, low public energy literacy, and weak supporting policies at the regional level. Through a thematic synthesis of the literature from the past five years, this study formulates a local energy ecosystem-based integration model that encompasses modular technology, multilevel policies, and community empowerment. These results are expected to serve as a strategic reference in promoting a just and sustainable energy transition in underdeveloped regions.

**Keywords**: Hybrid Energy, Literature Review, Remote Areas

## INTRODUCTION

Equitable and sustainable energy availability is a crucial foundation for economic and social development, yet access to electricity remains a significant challenge in remote areas. Long distances from distribution centers, difficult geographic terrain, and a lack of electricity infrastructure mean many remote areas remain off-grid. This situation limits access to basic services such as education, healthcare, and productive economic activities. This inequality not only reflects development inequalities but also poses long-term social sustainability issues (Achmadin et al., 2024).

On the other hand, remote areas possess relatively high potential for renewable energy resources that have not been optimally utilized. Resources such as consistent solar radiation throughout the year, stable wind speeds, and the potential for micro-hydro power from small rivers offer significant opportunities for local clean energy generation (Defi et al., 2025). However, minimal investment, technological limitations, and the low technical capacity of local communities are major obstacles to exploiting this potential. Therefore, a technological approach is needed that can bridge the gap between local resource availability and energy needs in a sustainable and adaptive manner to the local context.

Hybrid energy systems have emerged as a technical and economic solution that can improve the reliability and efficiency of energy supply in remote areas. These systems combine two or more renewable energy sources, such as solar panels, wind turbines, or micro-hydro power plants, with battery-based energy storage or even a diesel-based backup system. This approach allows for diversification of energy sources, thereby mitigating supply fluctuations that typically occur when relying solely on a single source. Furthermore, hybrid systems can reduce long-term operational costs and provide flexibility in electricity load management (Gombo et al., 2024).

Technologically, advances in smart controllers, energy storage, and the Internet of Things (IoT) are further enhancing the efficiency of hybrid systems in remote areas. The integration of these technologies enables real-time monitoring and management of energy systems, enabling local operators to make data-driven decisions. Predictive technology can also be used to anticipate weather fluctuations and automatically adjust energy distribution. This opens up significant opportunities for the digitalization of energy systems at the local level, previously considered impossible due to limited digital infrastructure in remote areas (El Balad, 2025).

However, implementing a hybrid system is not without various technical and non-technical challenges. Technical challenges include selecting the right system configuration, managing energy storage, and ensuring resilience to extreme climate conditions (Sinaga et al., 2021). Meanwhile, non-technical challenges include social aspects, such as local community acceptance; economic aspects, such as sustainable financing schemes; and institutional aspects related to system management by communities or local governments. Therefore, developing a hybrid system requires a holistic approach that focuses not only on technological aspects but also takes into account social dimensions and local policies.

In this regard, literature studies play a strategic role as an evaluative and exploratory basis for best practices in implementing hybrid energy systems around the world. Literature reviews enable researchers to identify proven effective energy integration models, assess success and failure factors, and understand the technical and social dynamics that influence the sustainability of renewable energy projects. By synthesizing various scientific publications and implementation reports, this study can provide a strong conceptual framework for designing contextual and applicable hybrid energy solutions for remote areas.

Furthermore, literature reviews also serve as tools for mapping research gaps and policy development needs. In many cases, there are inconsistencies between adopted technologies and local management capacity, leading to project failure in the long term. Therefore, through systematic literature analysis, researchers can formulate recommendations for a transdisciplinary approach that simultaneously encompasses technical, economic, social, and institutional aspects. This is particularly important in the context of remote areas with unique and complex characteristics.

Thus, integrating hybrid renewable energy systems in remote areas is not merely a technological challenge but also a discourse on inclusive and equitable energy transformation. Literature review is a crucial first step in this process, building a strong scientific foundation for decision-making at the planning and implementation levels. In the long term, the use of hybrid systems designed based on an evidence-based approach has the potential to create an adaptive, participatory energy transition model capable of supporting sustainable development in areas that have historically been disadvantaged in terms of energy access.

## METHOD

This study uses a qualitative approach with exploratory and analytical literature review methods to examine the integration of hybrid renewable energy systems in remote areas. Data were obtained from credible secondary literature, such as indexed journal articles, technical reports (IEA, IRENA, UNDP), policy documents, and publications from sustainable energy organizations. These were published within the last 5–10 years, relevant, with clear methodology, and written in Indonesian or English.

A literature search was conducted through Google Scholar, Scopus, and ScienceDirect using relevant keywords, Boolean techniques, and year and field filters. The results were screened using critical appraisal to assess quality and relevance. Analysis was conducted through content analysis and thematic synthesis, grouping themes such as hybrid technology models, technical challenges, socio-cultural factors, and policy aspects.

The thematic synthesis evaluated best practices, barriers, and the influence of local context on the success of hybrid systems, including their suitability for similar conditions in Indonesia. The validity of the results was ensured through source triangulation and transparent documentation of the research and analysis process to ensure repeatability and accountability. The research revealed knowledge gaps, such as the lack of hybrid models suited to remote geographic characteristics and a lack of community engagement. This study provides an overview of technological developments, challenges, and a conceptual framework to support a sustainable and inclusive energy transition in underdeveloped regions.

## RESULT AND DISCUSSION

### 1. Dynamics of Hybrid Energy System Implementation in Remote Areas

The implementation of hybrid energy systems in remote areas has become a strategic solution to address limited electricity access, particularly in areas not yet covered by the national electricity grid. Hybrid systems, which combine two or more renewable energy sources such as solar, wind, or micro-hydro power with backup sources such as diesel generators, are designed to improve the reliability and continuity of electricity supply. In practice, the configuration of these technologies depends heavily on geographical conditions and locally available natural resources. For example, in coastal areas with high wind potential, a solar-wind hybrid system is more efficient, while in mountainous areas with stable water flow, a solar-micro-hydro combination is more optimal.

Energy management strategies in hybrid systems are key to their operational success. The use of intelligent control systems and energy storage (such as lithium-ion batteries or BESS) allows for efficient load regulation and reduces reliance on non-renewable sources. However, the complexity of managing energy distribution and the need for routine maintenance require adequate local technical capacity. In many cases in Indonesia, successful implementation depends on local community participation and the sustainability of business models that support long-term maintenance. Several government programs, such as PLN's Village Electricity Program or the Special Allocation Fund (DAK) project, have implemented these systems, but challenges remain in monitoring, technical training, and spare parts provision (Syahputra & Rahmat, 2024).

Globally, case studies in countries such as India, Nepal, Kenya, and the Philippines demonstrate that the success of hybrid systems is often determined by a contextual approach—one tailored to community needs, resource potential, and the presence of strong local institutions. For example, in Nepal, the Pico Hydro project, combined with solar panels, successfully electrified remote villages at low cost and with high community participation. Conversely, in some parts of sub-Saharan Africa, hybrid systems have failed to operate sustainably due to weak maintenance systems and limited access to modern technology.

Geographic and climatic factors also influence the technical design of hybrid systems. In Indonesia, the main challenge lies in tropical conditions with high rainfall and unpredictable weather, which can reduce the efficiency of solar panels. On the other hand, eastern Indonesia, with its high solar radiation, is an ideal location for solar hybrid systems. System design must consider seasonal variations and the sustainability of supply from each source. For example, during a prolonged dry season, water supply for micro-hydro power can decrease drastically, necessitating backup energy through diesel or energy storage systems (Abdin et al., 2024).

One emerging innovative approach is the integration of the Internet of Things (IoT) for remote monitoring and control of hybrid systems. Through sensors and cloud-based platforms, operators can analyze system performance in real time and detect disruptions early. This is especially important in areas with difficult physical access, as it can reduce operational costs and repair time. Examples of successful IoT implementations include off-grid hybrid projects in Kalimantan and Papua, which have increased energy efficiency by up to 20% compared to conventional systems.

However, the implementation of hybrid systems still faces social and institutional challenges. Lack of public understanding of the technology, low energy literacy, and dependence on external parties are significant obstacles (Ali et al., 2025). Therefore, a holistic approach is needed that prioritizes not only technical aspects but also strengthens social and institutional capacity at the local level. Training local technicians, operational incentive schemes, and cooperative-based management models or village-owned enterprises (BUMDes) could be contextual solutions (Khan et al., 2025).

From a policy perspective, national regulations regarding renewable energy and village electrification need to be aligned with local dynamics so that hybrid system implementation is not merely a short-term project but a sustainable solution. The government can play a role in setting technical standards, providing initial subsidies, and establishing partnerships with the private sector and NGOs. In some regions, tripartite partnerships between the government and technology development communities have successfully created efficient and scalable replication models.

Ultimately, the dynamics of hybrid energy system implementation reflect the need for an integrative approach encompassing technical, social, economic, and policy aspects. An in-depth evaluation of each case study would be invaluable for generating cross-contextual learning, refining business models, and developing hybrid systems that are adaptive to challenges in remote areas.

### 2. Multidimensional Challenges in Hybrid System Development

The development of hybrid energy systems, particularly those combining solar and wind energy in remote areas of Indonesia, faces complex, interrelated, multidimensional challenges. These challenges encompass technical, economic, social, and institutional aspects that impact all project stages, from planning to operation. Technical barriers typically involve the quality of system components, such as inverters, batteries, and wind turbines, which often rely on imported products. This dependence not only increases initial costs but also raises issues with spare parts availability and the technology's suitability to local climate conditions, such as high humidity or unstable winds (Maghami et al., 2023).

Economically, developing hybrid systems requires significant upfront investment, often beyond the reach of local governments or communities. Limited access to inclusive and sustainable financing schemes leads to many projects stalling or remaining short-lived. Furthermore, immature business models and a lack of economic incentives discourage the private sector from participating in energy service delivery in underdeveloped regions. Therefore, collaborative funding schemes between the government, the private sector, and international donors are needed, enabling results-based financing or community microfinance (Rulinawaty et al., 2024).

From a social perspective, the low capacity of local human resources (HR) is a major obstacle to system operation and maintenance. The lack of adequate technical training often results in suboptimal hybrid systems, or even stalling due to minor damage that is not promptly repaired (Putra & Kurniawan, 2025). Furthermore, community acceptance of new technologies varies, influenced by cultural factors, knowledge, and perceptions of the system's long-term benefits. The lack of active community participation from the planning stage also contributes to a low sense of ownership and responsibility for the energy system.

Institutional challenges are equally significant, particularly concerning inter-agency coordination, the lack of technical regulations, and the lack of integration of hybrid energy systems into regional development plans. Many local governments lack a clear policy or regulatory framework to support renewable energy adoption. The lack of technical and institutional standards for managing hybrid systems has led to fragmented roles between the central government, regional governments, and service providers. In some cases, international grant projects operate without synergy with local policies, creating overlapping policies and duplication of resources (Zhang et al., 2024).

The long-term sustainability of hybrid systems also faces significant challenges, particularly in maintenance. Without a robust community-based maintenance system, many systems fail to survive beyond five years. The lack of a transparent and equitable service tariff mechanism also leads to insufficient operational costs. Therefore, it is crucial to develop an adaptive, community-based village energy management model that addresses not only technical aspects but also social equity and economic sustainability.

Addressing these challenges requires a cross-sectoral and transdisciplinary approach. This approach combines technological innovation with local capacity building, policy reform, and flexible financing strategies. Initiatives such as locally based training programs, the development of renewable energy logistics hubs, and the digitization of monitoring systems through the Internet of Things (IoT) can provide solutions to increase efficiency and community engagement (Gao et al., 2025). Furthermore, the application of co-design principles between technocrats and local communities can encourage more contextual and sustainable solutions.

Considering all these dimensions, it's clear that developing hybrid systems in remote areas is more than just installing technology. It's a transformative process that requires integrated interventions, from inclusive technical planning and supportive affirmative policies to the socio-economic empowerment of local communities. Without comprehensively addressing these multidimensional challenges, the risk of failure and inefficiency will remain high, and the ambitious goal of electrifying remote villages through renewable energy will be difficult to achieve.

## 3. Integration Model and Strategic Recommendations Based on Literature Study

In an effort to formulate a hybrid energy system integration model that is adaptive to conditions in remote areas, this study conducted a thematic synthesis of relevant scientific literature from the past five years. The results of the synthesis indicate that an integrative approach that considers technological, social, economic, and institutional variables is essential for addressing the complexity of energy challenges in underdeveloped regions. The remote geographic context, limited infrastructure access, and high operational costs make a monodisciplinary approach inadequate. Therefore, a conceptual model based on a local energy ecosystem is needed that prioritizes the principles of sustainability, energy independence, and resilience to environmental dynamics and climate change (Fadli & Syahputri, 2025).

From a technological perspective, the reviewed literature consistently emphasizes the effectiveness of solar and wind-based hybrid system configurations, enhanced by high-capacity battery-based energy storage systems (Irsan et al., 2025). However, the main challenges in implementing this technology lie in the volatility of power supply due to fluctuations in primary sources, degradation of storage efficiency, and the lack of an automated control system. In response to these challenges, the integration of Internet of Things (IoT) technology and smart energy management systems (SEMS) is crucial, as they enable real-time data-driven decision-making, early detection of system disruptions, and adaptive load optimization. Therefore, the technical aspects must be designed in a modular and flexible manner to be adapted to the location typology and scale of user needs.

Furthermore, energy management plays a crucial role in maintaining the continuity of energy services and the operational efficiency of the system. Demand-side management (DSM) models, which emphasize consumption management through education, peak load limiting, and progressive tariff incentive systems, have been shown to be effective in increasing user awareness of energy conservation. Studies also show that local microgrids managed collectively by communities or energy cooperatives yield better technical and social sustainability outcomes compared to systems that rely solely on external institutions (Wu et al., 2022). Therefore, energy integration models cannot be separated from the socio-cultural dimensions of local communities, who will serve as both operators and primary users (Suyatna et al., 2028).

From a policy perspective, the literature synthesis underscores the need for multi-level policies that support community-based energy transitions. Local governments have a strategic role in developing regulations that adapt to local contexts, including renewable energy project licensing, community asset protection, and fiscal incentives for independent energy projects (Nathan et al., 2022). Furthermore, the active role of national technical institutions in developing technical standards for hybrid systems is key to ensuring the quality and interoperability of system components. However, top-down policies must be combined with a bottom-up approach through participatory mechanisms and multi-actor dialogue to ensure social legitimacy and effective implementation.

The community empowerment dimension is a fundamental pillar of this integration model. Literature shows that renewable energy projects in remote areas that involve technical training, energy entrepreneurship incubation, and institutional support tend to be more successful in terms of long-term sustainability. Training schemes based on local technology transfer, along with support from universities or research institutions, can strengthen the technical capacity of communities to operate, maintain, and even replicate energy systems independently. Therefore, community empowerment is not merely a social strategy but an integral component of energy system resilience.

Based on the conceptual mapping generated from the literature study, the proposed integration model involves four main components that are synergistically interrelated, namely: (1) a modular hybrid technology configuration tailored to local potential, (2) a digital-based energy management system that enables continuous optimization, (3) a multi-scale policy framework that is responsive to local dynamics, and (4) a community empowerment strategy through training and participation in energy governance. This model is designed to be flexibly adopted in various remote areas, both in the highlands, islands, and border areas.

Furthermore, strategic recommendations derived from this model encompass several key areas. First, policymakers at the national level need to develop national technical guidelines for hybrid off-grid systems based on a local, participatory approach. Second, funding support should focus on blended finance schemes involving collaboration between the government, the private sector, and donor agencies. Third, community energy innovation centers should be established at the regional level to serve as hubs for training, technical maintenance, and model replication in other villages. Fourth, collaboration between local actors, academics, and external stakeholders should be facilitated through renewable energy collaborative platforms to encourage the dissemination of best practices and innovations.

Thus, the development of a hybrid energy system integration model based on this literature study is expected to serve as a conceptual and strategic reference in efforts to realize a just and inclusive energy transition in areas that have been marginalized from the conventional electricity grid (Trivedi et al., 2022). This model emphasizes the importance of a transdisciplinary approach, where technology, governance, and community are no longer isolated but integrated into a local energy ecosystem that is sustainable and resilient to future challenges.

## CONCLUSION

The implementation of hybrid energy systems in remote areas demonstrates the urgency of a transdisciplinary approach that synergistically combines technical, social, economic, and institutional dimensions. Hybrid systems that combine renewable energy sources with conventional reserves have been shown to improve electricity supply reliability, particularly when tailored to local geographic conditions and potential. The success of these systems is strongly influenced by efficient energy management strategies through intelligent storage and control technologies. However, technical challenges such as component quality, supply fluctuations, and spare parts availability remain significant obstacles. Limited funding, low public energy literacy, and institutional capacity gaps also complicate the development of these systems. Therefore, empowering local communities through technical training and participatory governance models is crucial for maintaining operational sustainability. Multilevel policies that respond to local dynamics are essential to strengthen the integration of hybrid energy systems into development planning. A literature synthesis shows that a local energy ecosystem-based approach is more effective than purely top-down interventions. Integration models involving modular technology, system digitalization, adaptive policies, and community empowerment have been shown to enhance long-term energy security. International and domestic case studies demonstrate the importance of co-design between technocrats, governments, and communities in generating contextual solutions. With flexible, collaborative, and locally driven system design, hybrid energy can be the foundation for a just energy transition in underdeveloped regions. Therefore, the development of this system is not simply an infrastructure project, but a transformational step toward national energy independence and equity.

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