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Challenges of Power Grid in Remote Areas and Their Alternative Solutions

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Abstract

Access to reliable electricity remains a significant global challenge, particularly in remote and isolated regions where geographical barriers, high infrastructure costs, and limited technical resources hinder the expansion of conventional power grids. In Indonesia, despite achieving a high national electrification rate, several frontier, outermost, and disadvantaged (3T) regions continue to experience limited access to electricity, adversely affecting social development, healthcare services, education, and local economic activities. This study aims to identify the principal challenges associated with power grid development in remote areas and to analyze alternative solutions based on sustainable renewable energy technologies. This research employed a qualitative descriptive approach through a literature review of scientific articles, government reports, and international energy publications related to rural electrification, renewable energy, and decentralized power systems. The findings reveal that the challenges of rural electrification are driven by interconnected factors, including difficult geographical conditions, high capital and operating costs, limited technical capacity, dependence on fossil fuels, and inadequate policy support. Renewable energy solutions, particularly solar photovoltaic (PV) systems, micro-hydropower systems, and hybrid microgrids, were identified as feasible alternatives for improving electricity access in remote communities. Furthermore, community participation, technical capacity building, and supportive government policies were identified as critical factors for ensuring long-term sustainability. This study concludes that integrated renewable energy-based electrification strategies provide a more sustainable and practical approach to addressing the challenges of electricity access in remote areas. The findings contribute to energy planning and policy development by providing recommendations for achieving equitable, reliable, and environmentally sustainable electricity access in remote regions.

INTRODUCTION

Electrical energy is an essential requirement for supporting modern society. Nearly every aspect of contemporary life, including education, healthcare, transportation, and economic activities, depends on a reliable electricity supply. In Indonesia, although the national electrification rate has exceeded 98%, several remote regions and 3T (frontier, outermost, and disadvantaged) areas still lack adequate access to electricity. This situation has contributed to persistent development disparities between urban and rural communities. People living in remote regions continue to face limited access to healthcare services, education, and productive economic activities because of inadequate electricity infrastructure (Vincent et al., 2024).

Therefore, examining the challenges of power grid development in remote areas, together with feasible alternative solutions, is essential for supporting national development planning (Ibekwe et al., 2024; Utoh et al., 2024).

The energy poverty experienced by communities in remote areas extends far beyond the inconvenience of limited electricity access (Day et al., 2016; Yadav et al., 2019). Without reliable electricity, healthcare facilities cannot operate essential medical equipment, students are unable to study after dark, and small businesses cannot operate productive machinery or refrigeration systems. According to the World Bank (2020), access to electricity is a fundamental prerequisite for sustainable development, and its absence perpetuates cycles of poverty and underdevelopment. For Indonesia, an archipelagic nation comprising more than 17,000 islands with diverse geographical conditions, achieving universal electricity access remains a particularly complex challenge.

The Indonesian government has made substantial progress in expanding electricity access through national initiatives, including the 35,000 MW electricity development program and various rural electrification programs. However, the remaining unelectrified communities are typically those located in areas where conventional grid expansion is technically difficult, economically unviable, or logistically challenging. These communities are commonly situated in mountainous regions, densely forested interior areas, or small isolated islands located far from the main electricity grid (Palit & Bandyopadhyay, 2016). Addressing their energy needs requires innovative technological solutions that are tailored to local geographical and socioeconomic conditions.

Renewable energy technologies have emerged as strategic alternatives for improving electricity access in remote regions (Denial, 2023; Holdmann et al., 2019). Solar photovoltaic (PV) systems, micro-hydropower systems, biomass energy, wind energy, and hybrid microgrids provide opportunities to develop decentralized electricity systems that utilize locally available energy resources. According to the International Renewable Energy Agency (IRENA), renewable energy technologies have experienced substantial cost reductions, particularly solar photovoltaic systems, whose global costs have declined significantly over the past decade (Burke & Stephens, 2018). These technological advances have improved the feasibility of implementing off-grid and hybrid renewable energy systems in remote communities. Solar PV systems are particularly suitable for regions with high solar irradiation, whereas micro-hydropower systems are well suited to mountainous areas with reliable water resources (Konduru et al., 2024; Syahputra & Soesanti, 2021). Consequently, renewable energy-based electrification represents not only a solution for improving electricity access but also a pathway toward sustainable rural development.

Previous studies have investigated various approaches to improving electricity access in developing regions. Chaurey and Kandpal (2010) examined decentralized photovoltaic-based rural electrification and emphasized the importance of renewable energy systems for communities where grid expansion is impractical. Similarly, Sovacool (2012) highlighted the potential of off-grid technologies to reduce energy poverty by providing affordable and locally managed electricity solutions. Bhattacharyya (2018) further discussed mini-grid development and emphasized that successful rural electrification requires appropriate business models, supportive policies, and community participation. These studies demonstrate that decentralized renewable energy systems have considerable potential; however, their successful implementation depends on technological, institutional, economic, and social factors that vary across geographical contexts.

Despite extensive research on renewable energy-based electrification, several knowledge gaps remain regarding the specific challenges and integrated solutions required for remote areas in Indonesia. Existing studies have often focused on individual technologies, such as solar PV systems or micro-hydropower systems, without comprehensively examining the interconnected barriers associated with geographical conditions, infrastructure costs, technical capacity, dependence on fossil fuels, and policy constraints. Furthermore, findings from studies conducted in other developing countries cannot always be directly applied to Indonesia because of its unique archipelagic geography, diverse natural resources, and administrative complexity. Therefore, a comprehensive analysis integrating technological, socioeconomic, and policy perspectives is needed to develop effective strategies for sustainable electrification in remote regions of Indonesia (Mandelli et al., 2014).

The urgency of this research is reinforced by the increasing demand for inclusive development and the transition toward low-carbon energy systems. Without effective electrification strategies, remote communities will continue to experience persistent development disparities compared with urban populations. Limited electricity access affects not only household welfare but also education, healthcare, entrepreneurship, and local economic productivity. In addition, continued dependence on diesel-based electricity generation is inconsistent with global commitments to reduce greenhouse gas emissions and promote sustainable energy transitions. Therefore, identifying feasible alternatives for electricity supply in remote areas is essential for supporting Indonesia's energy security, environmental sustainability, and equitable development objectives.

The novelty of this research lies in presenting a comprehensive framework that links the technical challenges of remote power grid development with renewable energy-based solutions within the Indonesian context. Rather than evaluating renewable energy technologies independently, this study integrates geographical, economic, technical, environmental, and policy dimensions to provide a multidimensional understanding of remote electrification challenges. The research also emphasizes the importance of combining renewable energy technologies, including solar PV systems, micro-hydropower systems, and hybrid microgrids, with community empowerment and supportive government policies. This integrated perspective contributes to the development of more practical and sustainable electrification strategies for isolated communities.

The objective of this study is to identify the principal challenges affecting electricity supply in remote areas, analyze renewable energy alternatives capable of addressing these challenges, and propose strategic recommendations for sustainable electrification. Specifically, the study examines the relationships among infrastructure limitations, economic feasibility, technological options, and institutional support in determining the success of rural electrification programs. Using a literature-based analytical approach, this research synthesizes evidence from scientific publications, government reports, and international energy studies to develop a comprehensive understanding of the challenges associated with electricity access in remote regions.

This research contributes both academically and practically to the advancement of sustainable rural electrification. From an academic perspective, the study enriches the literature on sustainable energy development by integrating technological and socioeconomic perspectives in addressing energy inequality. From a practical perspective, the findings provide guidance for policymakers, energy planners, researchers, and other stakeholders in designing renewable energy deployment strategies, community-based electricity management systems, and policy frameworks for remote regions. The implementation of these recommendations has the potential to improve the effectiveness of rural electrification programs, reduce dependence on fossil fuels, strengthen local energy independence, and promote equitable socioeconomic development. Ultimately, sustainable electrification strategies for remote areas can make a substantial contribution toward achieving universal electricity access and ensuring that remote communities benefit equitably from national development.

METHOD

This study employed a qualitative descriptive approach using a literature review to examine the challenges of electricity access in remote areas and identify alternative solutions based on renewable energy technologies. Relevant scientific publications, government reports, institutional documents, and international energy studies addressing rural electrification, renewable energy, off-grid systems, microgrids, and electricity infrastructure in remote regions were reviewed. Sources were selected purposively based on their relevance, credibility, methodological quality, and contribution to the research objectives. The reviewed literature included publications from international organizations, government agencies, and peer-reviewed journals.

Data were collected through a structured literature review and analyzed using thematic analysis. Information extracted from the selected sources was organized into key themes, including geographical challenges, infrastructure constraints, economic factors, technical capacity, dependence on fossil fuels, renewable energy alternatives, policy support, and community participation. The thematic findings were synthesized to develop a comprehensive understanding of the challenges associated with remote electrification and the potential of renewable energy-based solutions.

The analysis focused on examining the relationships among technological, economic, environmental, social, and policy factors influencing electricity access in remote areas. Particular attention was given to evaluating the feasibility of renewable energy technologies, including solar photovoltaic (PV) systems, micro-hydropower systems, and hybrid microgrids, as sustainable alternatives to conventional grid expansion. The synthesized findings were subsequently used to formulate strategic recommendations for sustainable electrification planning in remote regions.

RESULTS AND DISCUSSION

Geographical Conditions

A considerable number of remote regions in Indonesia are situated in mountainous areas, archipelagos, or dense forest zones. The establishment of transmission and distribution networks in such locations requires substantial financial resources and specialized technology. The rugged terrain makes construction of electrical poles and cables extremely challenging, while the remote location increases transportation costs for materials and equipment. In archipelagic regions, sea transportation adds further complexity and expense, and seasonal weather conditions can cause lengthy delays in construction activities.

Construction and Operational Costs

The development of conventional electricity network infrastructure in remote areas is frequently deemed uneconomical due to the relatively small population size. The cost per kilometer of transmission line in difficult terrain can be several times higher than in flat, accessible areas. Furthermore, ongoing operational costs including fuel supply for diesel generators, maintenance, and repairs are disproportionately high relative to the revenue generated from small and low-income consumer bases. This economic reality discourages private investment and places a heavy burden on state electricity company (PLN) finances.

Limited Human Resources (HR)

The scarcity of local technical personnel poses significant challenges to the maintenance of electricity networks. Most qualified electrical engineers and technicians prefer employment in urban centers where career opportunities and living standards are higher. Consequently, damage to electrical installations in remote areas often remains unrepaired for extended periods, sometimes weeks or months, causing prolonged power outages that severely impact community welfare. The lack of local capacity also means that external technical teams must be dispatched from distant cities, further increasing costs and response times.

Dependence on Fossil Fuels

In many remote areas across Indonesia, electricity generation continues to rely on diesel-powered generators (PLTD). These systems are costly to operate due to high and volatile diesel fuel prices, and the logistical challenges of transporting fuel to remote locations add further costs and supply reliability risks. Diesel generators also produce greenhouse gas emissions and local air pollution, contributing to environmental degradation. The dependence on imported fossil fuels also creates energy security vulnerabilities, as supply disruptions can leave communities without electricity for days or weeks.

Limitations in Policy and Government Support

Electrification programs have not yet comprehensively reached frontier, outermost, and underdeveloped regions (3T areas). Regulatory frameworks and incentive mechanisms for renewable energy investment in remote areas remain limited, creating barriers to private sector participation. Land acquisition and permitting processes can be lengthy and complicated, especially in areas with complex customary land tenure arrangements. Coordination between central and regional government agencies is sometimes inadequate, leading to delays and inefficiencies in project implementation. Additionally, funding allocation for rural electrification in national and regional government budgets does not always adequately reflect the scale of the challenge.

The findings of this study indicate that the challenges of electricity networks in remote areas are multidimensional, encompassing geographical, economic, technical, social, and policy dimensions. These challenges are deeply interconnected: geographical isolation drives up construction and operational costs, which in turn reduces the economic attractiveness of investment; limited technical human resources compromise the sustainability of installed systems; and inadequate policy frameworks fail to address the systemic barriers that prevent universal electrification. Understanding these interconnections is essential for developing effective and sustainable solutions.

Renewable energy technologies represent the most viable pathway to sustainable electrification in remote areas. Solar Power Plants (PLTS) are particularly suitable for regions with high solar irradiance, including much of Eastern Indonesia, such as Nusa Tenggara, Maluku, and Papua. Modern photovoltaic systems have seen dramatic cost reductions over the past decade, with the global average cost of utility-scale solar PV falling by more than 85% between 2010 and 2020 (IRENA, 2021). For remote communities, small-scale and modular PLTS systems can be sized to match local demand and expanded incrementally as community energy needs grow. The primary technical challenge—energy storage for nighttime and cloudy day operation—is increasingly being addressed by falling battery storage costs and improving battery technology.

Micro-Hydro Power Plants (PLTMH) offer excellent potential in mountainous regions with perennial river flows, such as in Sulawesi, Kalimantan, and Papua. PLTMH systems can provide reliable baseload power with very low fuel costs and minimal environmental impact when properly designed and sited. Their relatively low operational costs and long operational lifespans make them economically attractive despite higher initial capital costs. However, PLTMH development requires careful hydrological assessment to ensure adequate and consistent water flows, as well as environmental impact studies to protect downstream water users and aquatic ecosystems.

Off-grid microgrid and hybrid systems that combine multiple renewable energy sources with battery storage and backup diesel generation represent a particularly robust solution for communities that cannot be reached by the main grid. Hybrid systems can optimize energy generation from available local resources, reducing dependence on diesel fuel while maintaining reliable power supply. Advances in smart microgrid control systems now allow automated management of multiple energy sources, optimizing system efficiency and extending battery life. The relatively high initial capital costs of hybrid microgrid systems can be mitigated through government subsidies, concessional financing, and innovative business models such as energy-as-a-service arrangements.

Community empowerment is a critical success factor for sustainable electrification in remote areas. Technical training programs that equip local community members with skills to operate and maintain electricity systems reduce dependence on external technical support and create local employment opportunities. Community-based electricity management through village-owned enterprises (BUMDes) or energy cooperatives can ensure that systems are maintained according to local needs and that revenue from electricity tariffs is reinvested in system maintenance and improvement. Successful examples of community-managed electricity systems in Indonesia and other developing countries demonstrate that local ownership and management significantly improves system sustainability.

Government policy plays a crucial enabling role in creating the conditions for successful remote electrification (Barnes, 2011; Vincent et al., 2024). Investment subsidies and tax incentives for renewable energy development in remote areas can help overcome the economic barriers to private sector investment. Streamlining land acquisition and permitting processes for electrification projects can reduce delays and transaction costs. Strengthening coordination mechanisms between central and regional governments, PLN, and other stakeholders can improve planning and implementation efficiency. International cooperation and development assistance can provide both financial resources and technical expertise to support ambitious rural electrification programs (Amaefula, 2024).

The social and behavioral dimensions of remote electrification deserve greater attention. In some communities, low awareness of the benefits of renewable energy, cultural preferences for familiar technologies, and concerns about the reliability of new systems can create resistance to change. Effective community engagement processes that involve local leaders, explain the benefits and limitations of proposed technologies, and address community concerns are essential for building the social acceptance necessary for project success. Gender-sensitive approaches that ensure women's voices are heard in energy planning processes can also improve project outcomes and ensure that the benefits of electrification reach all community members equitably.

CONCLUSION

The principal challenges to electricity access in Indonesia's remote areas include geographical isolation, high capital and operating costs, limited technical capacity, dependence on costly and environmentally unsustainable fossil fuels, and inadequate policy and regulatory support. These challenges are interconnected and mutually reinforcing, requiring comprehensive and integrated solutions rather than isolated technological or policy interventions.

Renewable energy-based solutions, particularly Pembangkit Listrik Tenaga Surya (PLTS; solar photovoltaic [PV] systems) and Pembangkit Listrik Tenaga Mikrohidro (PLTMH; micro-hydropower systems), represent the most suitable alternatives for addressing these challenges in many remote communities. Hybrid microgrids that integrate multiple renewable energy sources with battery energy storage systems (BESS) can provide reliable, resilient, and sustainable electricity to communities beyond the reach of the main power grid. The continued decline in the cost of renewable energy technologies has further improved the economic viability of these solutions, even in geographically challenging locations.

Government support through investment incentives, streamlined permitting processes, stronger interagency coordination, and more effective regulatory frameworks is essential to accelerate rural electrification. Community participation, including technical capacity building and community-based operation and maintenance, is equally important for ensuring the long-term sustainability of electrification programs. In addition, public-private partnerships can mobilize financial resources, technological expertise, and implementation capacity to complement government initiatives. Through coordinated collaboration among government institutions, local communities, the private sector, and international partners, Indonesia can advance toward universal electricity access and ensure that all citizens benefit from the economic and social opportunities enabled by reliable and sustainable electricity.

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