

Optimization of Solar and Wind Hybrid Energy System with IoT Integration for Remote Areas in Indonesia

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Received: May 09, 2025

Accepted: June 22, 2025

Revised : May 19, 2025

Published: June 30, 2025

ABSTRACT

Limited access to electricity in remote areas of Indonesia reflects complex structural issues, including geographic constraints, policy inequalities, and the low effectiveness of centralized approaches. Thousands of villages in the 3T (Disadvantaged, Frontier, and Outermost) regions still do not enjoy reliable electricity, hampering socio-economic development and reinforcing the cycle of poverty. Although Indonesia has great potential for renewable energy—such as solar and wind—its use is still minimal due to infrastructure constraints, investment, and non-contextual development approaches. In this context, a hybrid solar-wind energy system integrated with Internet of Things (IoT) technology offers an efficient and sustainable decentralized solution. IoT enables real-time monitoring, predictive maintenance, and data-driven energy management, which are critical in remote areas with limited technicians and physical access. This study uses a qualitative approach through a literature review to examine the challenges, potential, and policy relevance in developing IoT-based renewable energy systems. The results of the analysis show that transforming energy systems in marginalized areas requires not only technological innovation, but also a paradigm shift towards inclusive energy justice. Therefore, strengthening local capacity and integrating context-based policies are key to realizing a fair, reliable and sustainable energy system in Indonesia.

Keywords: : Hybrid Energy; IoT Integration; Remote Electrification

INTRODUCTION

Limited access to electricity in remote areas of Indonesia is a structural problem that stems not only from geographical constraints, but also from the imbalance in national energy infrastructure development policies. Data from the National Energy General Plan (RUEN) shows that there are still thousands of villages in the outermost and most disadvantaged areas that do not have reliable electricity, most of which are spread across Eastern Indonesia. This indicates a systemic failure in PLN's centralized approach that tends to focus on centers of high energy demand, while areas with low economic value are often neglected. In the context of energy justice, this exacerbates socio-economic inequality between regions and reinforces the cycle of structural poverty.

Furthermore, the impact of limited access to electricity cannot be reduced to mere technical deficiencies, but must be seen as a multidimensional barrier to human development. A study by the IEA (2019) in Mursid et al (2021) confirms that access to modern energy is directly correlated with increased literacy, health services, and economic productivity. In areas without electricity, nighttime learning activities are disrupted, basic health services including vaccine storage or use of medical devices—become impossible, and local economic actors cannot develop digital-based businesses



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or cool crops. Therefore, conventional approaches to rural electrification are no longer adequate. A decentralized solution based on technology that is adaptive to local conditions is needed, such as a hybrid solar and wind energy system, which is able to meet energy needs sustainably outside the scope of the main grid (Achmadin et al., 2024).

Although Indonesia's renewable energy potential is very large, around 207.8 GW from solar power and 60.6 GW from wind power according to data from the Ministry of Energy and Mineral Resources (2023), its realization is still very minimal. The use of solar and wind energy in Indonesia in 2022 was recorded as having only reached less than 1% of the total national potential. This inequality shows the existence of structural obstacles, ranging from unpreparedness of infrastructure, low investment in technology, to dependence on a centralized fossil-based power generation model. Ironically, the areas that need alternative energy systems the most, such as East Nusa Tenggara, Maluku, and Papua, actually have the best solar radiation and wind speed potential nationally. This indicates that the energy development approach so far has not been able to answer the actual needs of people in marginal areas.

Even more problematic, most efforts to utilize renewable energy in Indonesia are still short-term projects and symbolically oriented, rather than aiming for long-term sustainability. Many solar and wind power installations are abandoned because they are not accompanied by adequate monitoring and load management systems. In this context, hybrid solar-wind technology integrated with the Internet of Things (IoT) is a strategic answer. Hybrid systems enable a more stable energy supply by utilizing the complementarity of resources: when sunlight weakens, wind energy can take over, and vice versa. IoT integration adds a layer of efficiency because it allows remote monitoring, load prediction, and automatic and adaptive disturbance detection (Harianto & Karjadi, 2025). Thus, optimizing renewable energy potential in remote areas is not only about generating technology, but also about intelligent systems that can guarantee long-term sustainability and reliability.

The integration of Internet of Things (IoT) technology in hybrid energy systems in remote areas is not only a complement, but an essential element in creating an adaptive, efficient, and sustainable system. IoT allows smart sensors to monitor the condition of solar panels, wind turbines, storage batteries, and consumption loads in real-time and based on data. According to research by Hadi et al (2025), IoT-based renewable energy systems can increase operational efficiency by up to 25% and extend the life of the system through early detection of damage. Without this technology, many systems in remote areas fail to operate optimally because there is no continuous monitoring or rapid response to technical disruptions.

Moreover, IoT plays a strategic role in decentralizing energy systems and strengthening local community resilience. With a cloud-based dashboard or mobile application, technicians or even local communities can access system performance data and make decisions directly, without having to wait for intervention from the center. This reduces dependence on external technicians and speeds up the recovery process when disruptions occur. However, challenges still remain, especially in terms of data security, the need for stable internet connectivity, and the initial cost of IoT integration (Muhtadi et al., 2025). Therefore, the design of an IoT system for remote areas must consider local conditions, such as the availability of LoRa networks, edge computing, and technical training for residents. With a contextual approach, IoT is not only a technical tool, but also a catalyst for community-based energy system transformation in 3T (Disadvantaged, Frontier, and Outermost) areas.

In the context of the national energy transition, the development of a hybrid system based on renewable energy supported by IoT technology in remote areas should

not only be considered as a technical solution, but as a political instrument for inclusive and equitable development. The national energy mix target of 23% renewable energy by 2025 as stated in Presidential Regulation No. 22 of 2017 concerning RUEN will not be achieved without serious decentralization of the energy system. However, to date, the realization of this policy is still uneven, with clean energy investments and projects being mostly centralized in urban areas and large industries. This shows a gap in implementation between the rhetoric of the energy transition and the reality on the ground, where communities in disadvantaged areas are still missing systematic attention in the national decarbonization agenda.

Furthermore, a sustainable energy transition approach must be in line with the principles of the Sustainable Development Goals (SDGs), especially SDG 7 (Affordable and Clean Energy), SDG 10 (Reduced Inequality), and SDG 13 (Addressing Climate Change) (Gaol & Tjenreng, 2025). An IoT-integrated solar-wind hybrid system can play a dual role in providing access to clean energy, as well as encouraging local economic independence and climate adaptation through carbon emission reduction. A study by UN ESCAP (2020) emphasized that renewable energy development in Southeast Asia will be effective only if it takes into account aspects of social justice and local context. This means that the success of this system is not only measured by technical capacity or emission reduction, but by how far it can strengthen community participation, create green jobs, and reduce dependence on an exclusive and centralized energy system.

METHOD

The research method used in this study is qualitative research with a literature review approach. This approach was chosen to explore, review, and critique various research results, policy reports, and relevant technical documents related to the optimization of a hybrid solar and wind energy system integrated with Internet of Things (IoT) technology, especially in the context of remote areas in Indonesia.

This research will utilize secondary scientific sources that include reputable international journals (such as *Renewable Energy*, *Energy Policy*, and *Renewable and Sustainable Energy Reviews*), government agency reports (e.g. Ministry of Energy and Mineral Resources, Bappenas), national policy documents (such as RUEN and RUKN), and publications from international organizations (such as IEA, UN ESCAP, and World Bank). The analysis technique used is qualitative thematic analysis, where researchers will identify key themes such as challenges of electrification in remote areas, local renewable energy potential, the role of IoT in decentralized energy systems, and the relevance of national energy policies. Furthermore, these findings will be critiqued in the context of effectiveness, sustainability, and energy equity. This approach allows researchers to build strong conceptual arguments and provide a basis for evidence-based implementation and policy recommendations in the development of hybrid renewable systems in marginal areas of Indonesia.

RESULT AND DISCUSSION

1. Energy Access Gap Analysis and Electrification Challenges in Remote Areas

To strengthen the analysis of energy access gaps and electrification challenges in remote areas of Indonesia, a number of scientific studies provide relevant empirical foundations. A study by Sansuadi (2025) shows that access to electricity has a strong correlation with increased household income, access to education, and quality of health services. In the Indonesian context, Harianto & Karjadi (2024) emphasized that the main obstacle to electrification in remote areas is the incompatibility of PLN's top-down

approach with local geographic and socio-economic conditions. They noted that PLN's electricity network tends to be developed based on economic efficiency and settlement density, leaving behind areas with scattered settlements and difficult geographic access.

Technically, research by Wardhana et al (2019) in his book highlights that decentralized energy solutions, such as hybrid solar and wind power systems, offer high effectiveness in overcoming energy inequality in 3T areas. The study shows that off-grid systems with smart controller integration and energy storage can reduce dependence on PLN infrastructure and provide higher supply reliability in locations with limited access. Furthermore, the IEA (International Energy Agency, 2022) emphasizes that renewable energy-based electrification in remote areas not only accelerates the achievement of SDG 7 (clean and affordable energy) targets, but also plays a role in reducing carbon emissions and increasing local energy independence. Therefore, this scientific approach supports the urgency of building a contextual, participatory, and local potential-based alternative energy system as a solution to electrification stagnation in Indonesia's underdeveloped regions.

Indonesia's geographical condition as an archipelagic country is a structural factor that greatly complicates the electrification process in remote areas. The national electricity infrastructure, which was built with a centralized approach through the PLN interconnection network, faces major challenges in reaching areas with small islands, extreme mountainous topography, and limited transportation access. For example, Ali & Jang (2020) emphasized that the cost of building an electricity network in an archipelagic region can reach 3-5 times that in the mainland, so it is considered economically unfeasible. Reliance on the long-distance transmission model not only increases energy losses (transmission losses) but also creates spatial inequality in the distribution of infrastructure development. As a result, many villages in Eastern Indonesia and border areas still rely on diesel-fueled generators which are inefficient, expensive, and pollute the environment. This is in line with findings from the ADB (Asian Development Bank, 2019) which states that investment in conventional distribution systems is less effective for areas with low population density and high geographic challenges.

In this context, the development of community-based renewable energy systems is becoming an increasingly technically and socially relevant solution. The decentralized approach through microgrids or stand-alone renewable energy systems not only reduces dependence on the PLN network, but also opens up space for local community participation in the management and maintenance of energy systems. Research by Ningsih & Syalikha (2024) shows that the success of a decentralized energy system is highly dependent on the suitability of technology to the local context, as well as the support of policies and technical capacity of the community. In addition, the potential of local resources such as solar, wind, and biomass energy is abundant in many 3T areas, but has not been optimally utilized due to the lack of integrated planning and cross-sectoral approaches. This is reinforced by the study of Atifoqkymin (2024) which states that small-scale renewable energy systems designed with a local needs-based approach can increase the reliability of energy services, encourage microeconomic growth, and strengthen community resilience to climate change and energy supply disruptions. Thus, a scientific and contextual approach to alternative energy development is not only a technical solution, but also an inclusive sustainable development strategy.

2. Potential and Technological Challenges in the Implementation of Solar-Wind Hybrid Energy Systems

Indonesia as a tropical archipelagic country located on the equator has a climate advantage that supports the development of renewable energy, especially solar and wind energy. Data from the Global Solar Atlas (World Bank, 2020) shows that the level of solar radiation in most parts of Indonesia ranges from 4 to 5.5 kWh/m²/day, which is relatively high and stable throughout the year. In addition, although wind speeds in Indonesia are relatively lower than subtropical countries, several areas such as East Nusa Tenggara, South Sulawesi, and the southern coast of Java have average wind speeds of between 5–7 m/s at a height of 50 meters, as reported in the Global Wind Atlas (IRENA, 2021). This makes the solar-wind hybrid system an ideal approach to harnessing energy potential simultaneously, with complementary characteristics—wind tends to be strong at night or when it is cloudy, while the sun is at its maximum during bright days (Syahputra & Rahmat, 2024).

However, this potential is overshadowed by various technological and structural challenges. One of the main obstacles is the high initial investment costs, especially for energy storage systems (batteries), hybrid controls, and wind turbines with corrosion-resistant designs. According to the IEA (International Energy Agency, 2022), the price of a hybrid system is still 30–50% more expensive than a single system, due to the complexity of integration and the need for additional components. In Indonesia, this condition is exacerbated by the dependence on imported components and the absence of microfinance schemes for remote villages. In addition, research by Afif & Martin (2022) shows that renewable energy devices in tropical areas experience decreased performance due to high humidity, extreme temperatures, and sea air salinity, which accelerate material degradation, especially in conventional wind turbines and solar panels.

From an operational technical perspective, the variability of energy output from two intermittent sources poses new challenges. A study by Babaremu et al (2022) emphasized that the combination of solar and wind energy requires a precise control system to maintain the stability of the microgrid, as well as real-time load regulation. The role of Internet of Things (IoT) and artificial intelligence (AI) technologies has been extensively studied, such as in research by Charles & Majid (2024) which concluded that AI-based hybrid systems can increase efficiency by up to 18% and reduce power losses due to weather fluctuations. However, the challenges of implementing this technology in Indonesia include the lack of communication networks in 3T (underdeveloped, outermost, and remote) areas, as well as the gap in the technical capacity of local human resources in understanding automatic control systems and maintenance.

Furthermore, inequality in technology transfer and lack of data-based policy support are long-term obstacles. A study by Ahmed et al (2024) in Renewable Energy Focus states that hybrid projects in Indonesia tend to be successful when accompanied by community technical training, partnerships with local universities, and adaptation of system design to local socio-cultural characteristics. Without this participatory approach, many projects end up as dead infrastructure (stranded assets) due to maintenance failure or social rejection. Therefore, in addition to technological interventions, a multi-sector strategy is needed including fiscal policies, financing incentives, increasing human resource capacity, and integrating regional energy policies so that the great potential of solar and wind energy is truly realized in a fair and sustainable manner.

3. The Role of Internet of Things (IoT) Technology in the Efficiency, Monitoring, and Sustainability of Decentralized Energy Systems

Internet of Things (IoT) technology plays a crucial role in strengthening the efficiency and reliability of decentralized energy systems, especially those based on renewable energy such as solar-wind hybrid systems. With the ability to digitally connect various devices and collect data in real time, IoT enables the process of continuously monitoring the operational conditions of energy systems, including solar panel output, wind speed, battery capacity, ambient temperature, and household or community energy consumption loads. Through this data, the system can automatically regulate energy distribution, optimize the use of energy sources, and minimize unnecessary energy waste. The use of IoT-based sensors and machine learning algorithms also enables early detection of disturbances or damage, such as inverter failure, decreased panel efficiency due to dirt, or anomalies in wind turbines, so that mitigation steps can be taken immediately before total damage occurs (Prawiyogi & Anwar, 2023; Khatua et al., 2020)

Another advantage of IoT in the context of energy sustainability in remote areas is its ability to support remote management and automated decision-making without requiring the physical presence of technicians, which is often a major obstacle in the context of 3T (Disadvantaged, Frontier, and Outermost) areas. IoT-based systems integrated with cloud computing and energy management dashboards can provide full control to operators, even from large cities, to monitor and manage systems on small islands or isolated mountains. In addition, this approach is in line with the concept of social sustainability, as it allows local communities to be involved in understanding and utilizing their energy data through a simple interface, thereby fostering energy literacy and active participation in system management. Studies such as those conducted by Kumendong & Pawarangan (2025) show that the implementation of IoT in renewable energy systems not only increases technical efficiency but also encourages long-term system sustainability. However, Indonesia's readiness to adopt this model still faces challenges in terms of uneven internet network infrastructure, limited local human resource capacity, and the need to adapt global technology standards to the local context. Therefore, IoT adoption must be carried out gradually and based on pilot models that are adaptive to Indonesia's needs and geographical conditions.

The application of IoT technology in decentralized energy systems also opens up great opportunities in terms of predictive maintenance, which can significantly reduce long-term operational costs. By continuously collecting and analyzing data, the system can identify damage patterns before functional failure occurs. This is especially important in remote areas that often experience logistical constraints and access to technical services. Research by Najib & Sulisty (2020) shows that an IoT-based monitoring system equipped with a predictive algorithm can reduce the frequency of system failures by up to 35% and increase system uptime by up to 20%. This improvement not only has an impact on technical sustainability but also strengthens local communities' trust in renewable energy technology as the main solution to their electricity needs.

Furthermore, IoT integration also plays a role in supporting demand-side management (DSM), a more efficient energy load management strategy by adjusting demand to supply availability. In areas with fluctuating solar-wind hybrid systems, IoT-based DSM enables automatic scheduling of electrical appliance usage at the best time, for example, when solar power is high during the day. This system can also prioritize essential loads such as lighting and water pumps, while delaying non-critical loads when energy supply is limited. A study by Nursita et al (2025) showed that implementing an IoT-based DSM strategy can reduce peak energy consumption by up to 25% and extend the battery life of the storage system. The practical implications of this strategy are

particularly relevant for Indonesia, where limited energy storage capacity and high battery costs are major obstacles to the expansion of renewable energy systems in remote villages. Therefore, the success of IoT implementation depends not only on the sophistication of its technology, but also on supporting policies, community training, and business models that are inclusive of local communities.

CONCLUSION

Analysis of energy access gaps and electrification challenges in remote areas of Indonesia reveals multidimensional issues that include geographic, technological, structural, and socio-economic barriers. Scientific studies show that the limitations of conventional electricity networks and PLN's top-down approach are unable to reach areas with complex geographic conditions and scattered settlements. This is exacerbated by high infrastructure costs and low efficiency of diesel-based systems that are still widely used in the 3T region. In this context, decentralized renewable energy systems, especially solar-wind hybrids, emerge as a more relevant and sustainable alternative solution. Indonesia's abundant natural potential supports the implementation of this system, but it is still overshadowed by technical challenges such as device degradation due to the tropical climate, the need for advanced storage technology, and complex system integration. The use of IoT technology in this system plays an important role in increasing efficiency, real-time monitoring, and predictive maintenance, as well as enabling remote control and intelligent load management. However, the success of this technology is highly dependent on the readiness of digital infrastructure, technical training of the community, and cross-sectoral policy support that is adaptive to local conditions. Therefore, to close the energy access gap in a fair and sustainable manner, a paradigm transformation of electrification is needed that places contextual technology, community participation, and local potential as the main foundation.

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