Maximizing Renewable Energy Assets in a Tourism Village in Yogyakarta, Indonesia

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Abstract. The pursuit of energy independence often relies on decentralized Renewable Energy Technology (RET) systems. This study examines the performance gap between installed potential and actual utilization of village-scale renewable energy system in Desa Donoharjo, Sleman, Yogyakarta, recognized as an Independent Energy Village (*Desa Energi Berdikari*). Although the village processes considerable renewable resources and supporting infrastructure, several systems operate below their optimal potential, raising concerns regarding their long-term sustainability and effectiveness. A mixed-method approach combined descriptive-comparative performance analysis of installed capacity and actual utilization with field observations and semi-structured interviews, followed by thematic analysis and data triangulation. The results reveal varying performance levels across the renewable energy systems. The solar photovoltaic system operates close to its expected potential, indicating relatively effective adoption and management. In contrast, the biodigester system demonstrates a substantial utilization gap between estimated and actual energy output. The findings indicate that the main constraints are socio-technical rather than purely technological, including limited technical skills, reliance on manual operational practices, an insufficient monitoring system, and delayed maintenance. Overall, the study concludes that the effectiveness of village-scale renewable energy initiatives depends not only on technological availability but also on the readiness of the local socio-technical system. Strengthening local technical capacity, improving monitoring mechanisms, and enhancing community-based operational management are essential to optimize system performance and ensure the long-term sustainability of renewable energy development in rural communities.

Keywords: Community-based energy management, Performance gap, Renewable energy systems, rural energy transition, socio-technical capacity

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1 Introduction

Developing countries face high vulnerability to climate and energy crises due to centralized fossil-fuel–based energy systems and limited socio-economic capacity [1]. These conditions have stimulated the emergence of Community Renewable Energy (CRE) initiatives as a solution to structural challenges such as high transmission and distribution losses, grid congestion, and increasing peak-load energy demand. In Indonesia, the development of CRE aligns with national commitments under the Second NDC (2025) [2], which targets peak emissions by 2030 and net-zero emissions by 2060. However, on-the-ground implementation remains constrained by continued dependence on fossil fuels, highlighting the need for decentralized energy approaches based on local potential and oriented toward energy justice [3].

The tourism sector, particularly in rural areas, has become an important driver of renewable energy adoption [4]. Rapid growth in homestays, micro, small, and medium-sized enterprises (MSMEs), and tourism-related activities has increased local energy demand, creating structural incentives for communities to transition toward clean energy sources. Renewable energy also supports green tourism branding strategies, which are increasingly valued by environmentally conscious travelers. The Special Region of Yogyakarta is among the provinces with the highest tourist visitation rates in Indonesia and is predominantly characterized by community-based and sustainable tourism destinations [5]. This condition reinforces the relevance of decentralized renewable energy systems to support tourism activities while strengthening local economic resilience. The region possesses significant potential through the availability of solar energy, biomass, and micro-hydropower resources, supported by strong social capacity as an education-oriented region. Regulatory frameworks, such as Regional Regulation of Yogyakarta Special Region No. 15/2018 and Presidential Regulation No. 11/2023, further provide opportunities for village-owned enterprises (BUMDes) and community groups to participate in village-level energy management.

Despite the increasingly supportive ecosystem, numerous studies indicate that the sustainability of rural renewable energy projects remains low due to weak local institutional capacity, limited community ownership, and heavy reliance on external funding [6]. This situation is also evident in Tunjung Tourism Village, Donoharjo, which has considerable renewable energy potential but has not yet been able to develop it independently. To date, few studies have examined how tourism dynamics influence renewable energy adoption decisions in tourism villages or how the roles of village institutions such as BUMDes, cooperatives, and tourism management bodies shape the long-term sustainability of community energy systems. This study seeks to address this gap by analysing the relationships between tourism development, local governance, and the sustainability of community-based energy transitions, thereby contributing to the development of more inclusive and sustainable village-level energy transition models in Indonesia.

2 Methodology

This study employs a mixed-method case study approach to examine the gap between installed renewable energy potential and actual operational performance in Desa Donoharjo Sleman, Yogyakarta, Indonesia. The methodology integrates qualitative and descriptive quantitative techniques to capture both technical and operational dimensions of village-scale renewable energy implementation.

2.1 Research Design

This research was conducted in Donoharjo Village, with the study location shown in **Fig. 1**, and was designed as an applied case study focusing on the post-installation and operational phases of decentralized renewable energy systems (Solar Power Plants [PLTS] and Fixed Dome Biogas) as part of an Independent Energy Village. This design suits identifying implementation gaps in operational management, human resource capacity, institutional arrangements, and procedural practices, rather than physical infrastructure or resource limitations. By examining real-world operations, the study generates practical insights into constraints on effective utilization.

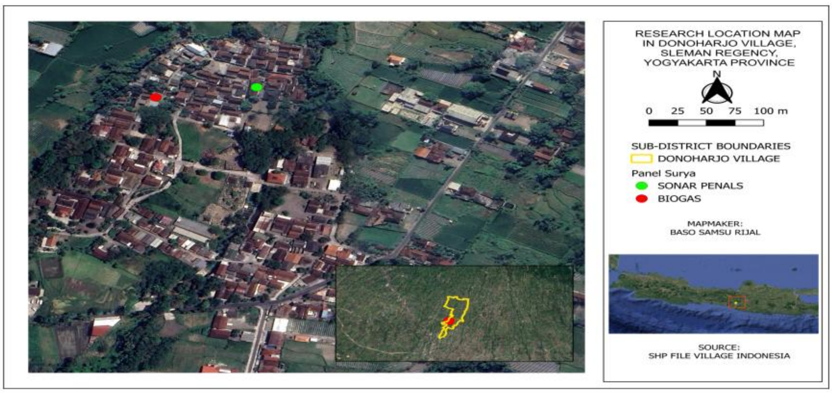

Fig. 1. Research Location Map

2.2 Data Collection Methods

Data were collected during a site visit from 5 to 19 December 2025 via field observations, semi-structured interviews, and targeted inventories. Primary sources included:

- Renewable Energy Inventory: Direct observation of PLTS (photovoltaic modules, inverters, battery storage, distribution networks) and Fixed Dome Biogas (feedstock availability, digester condition) systems, documenting installed capacity, configuration, utilization patterns, downtime frequency, and maintenance practices via operator reports and Pertamina technical input. Assessments used indicative operational conditions (e.g., system status, reliability for household cooking/electricity) due to absent metering/logs.
- Human Resource and Procedures Inventory: Interviews with local operators, village stakeholders, UGM student initiators, and Pertamina personnel, plus observations of daily practices, covering operator numbers/roles, training, O&M tasks, maintenance frequency, fault response times, and reliance on external support.

This approach evaluates operational effectiveness under real management conditions.

2.3 Data Analysis

A descriptive-comparative approach contrasted the installed capacity and design functions of the RE systems with their observed utilization and operational continuity to quantify potential performance gaps. Quantitative estimations were derived using several basic energy conversion formulas. First, the amount of electricity corresponding to the emission reduction was estimated using the relation energy = emission/emission factor, while the average solar PV productivity in Indonesia was assumed to be 1kWp = 1400 kWh/year [4]. Solar irradiation data expressed in annual units were converted into daily values using daily irradiation = annual irradiation/365. Furthermore, the expected daily electricity generation from the solar PV system was estimated using the concept of Peak Sun Hours (PSH) with the equation *E* = ⟩ x *PSH* x /, where *E* represents daily electricity production (kWh/day), ⟩ is the installed PV capacity (kWp), *PSH* is the effective solar irradiation time (hours/day), and / is the system efficiency factor (typically 0.75-0.85 to account for system losses) [7]. The average PSH value in Indonesia was assumed to be approximately 4.5 hours/day [8]. In parallel, thematic analysis of qualitative interview data identified recurring constraints such as manual monitoring, reactive maintenance practices, and limited technical skills. Triangulations of system inventories, field observations, and interview results were conducted to enhance the validity and robustness of the findings.

2.4 Analytical Framework

The framework links installed capacity, operational practices, and human resources to explain underperformance, emphasizing managerial/capacity constraints over resource availability. It identifies interventions like capacity-building, institutional strengthening, and automated monitoring. Although the field visit was conducted over five days, the interview and observation were conducted approximately in 2 weeks. The study also evaluates renewable energy systems that have been operating for several years. Therefore, the analysis focuses on operational conditions, maintenance records, and stakeholder experiences accumulated since the installation phase.

3 Results and Discussion

Based on findings from Desa Donoharjo, it is evident that community-based renewable energy projects, particularly the implementation of solar panels **(Fig. 2)** and biodigester energy **(Fig. 3)**, are operating far below their optimal capacities. Despite this, based on Sobi UGM calculation as a project pioneer, the village possesses strong renewable energy resources, such as organic waste from livestock of approximately 60–80 kg/day, which can produce the equivalent of 3 kg of LPG per day, as well as high solar radiation potential of 1101.2 kWh/m² for solar-based energy development.

Fig. 2. Solar Panel and

Fig. 3. Biodigester Energy

Moreover, this village also has a strong social model in implementing new projects or programs because the culture of *gotong royong* and coordination among village communities are still sustained and well established; it is also supported by the experiences of this village in becoming a tourism village since 2001 [9]. However, the comparison between the installed RE capacity and its actual operational utilization in the village is presented in **Table 1** to highlight the existing implementation gap.

Table 1. Installed Capacity versus Actual Utilization

System	Installed Capacity	Estimated Potential	Actual Utilization	Performance Gap
Solar PV	0.9-1.4 kWp	3.02 kWh/day	3.04 kWh/day	-0.02 kWh/day (-0.66%)
Biodigester	10 m^3	3 kg LPG equivalent/day	1.15-1.84 kg LPG/day	1.16-1.85 kg LPG/day (38.7-61.7%)

The implementation of RE demonstrates how three key components of social investment drive positive transformation and impact on RE implementation within the village. Mutual cooperation (Gotong Royong) transforms raw RE material (organic waste and solar radiation) into new energy sources, leading to the finding of new energy alternatives, improved villagers' knowledge and capacity in RE implementation, and greater togetherness in solving RE challenges. Regular community workshops and training facilitate the transfer of technology and research opportunities, which in turn results in the optimization of RE programs and strengthens the community's technical capacity to operate RE systems. This was reflected in the solar PV system performance, where the actual utilization (3.04 kWh/day) slightly exceeds the estimated potential (3.02 kWh/day), indicating a very small performance gap (-0.66%). This result suggests that the solar energy technology has been relatively well adopted and managed by the local community.

Lastly, the village's establishment as a tourism village since 2001 leverages new tourism assets as a package, impacting the community by creating green tourism branding, making it easier to adapt to new technology, and increasing overall tourist attraction. Through these social investments, the village secures not only the adoption of RE technology but also broader socio-economic and sustainable development. The success of the renewable energy projects is expected to be a new asset for the village tourism package to boost tourist visits. However, the comparison between estimated potential and actual utilization reveals different performance patterns among the renewable energy systems. While the solar PV system performs close to its technical potential, the biodigester system shows a considerable performance gap. With an estimated potential of about 3 kg LPG equivalent per day, the actual utilization ranges only between 1.15-1.84 kg LPG equivalent per day, indicating a performance gap of approximately 38.7-61.7%. This discrepancy confirms that the main challenge is not merely technological availability but also socio-technical constraints, especially in the lack of skilled human resources and the difficulties of system operation for local communities that can be a barrier in implementing green tourism villages.

This result is important in mirroring the general pattern of implementation in most developing countries such that technology is sometimes available; however, the management capacity, training, and operational infrastructure are not following the technology complexity [10]. The literature regarding off-grid renewable energy mentioned about the failed project was not due to inadequate hardware but due to lack of management system and technical knowledge to support its long-term operation [10]. Therefore, this study emphasized that the success of the EBT technology can't be separated from the readiness of the social and technical ecosystem in using the technology.

These findings highlight that renewable energy implementation in rural tourism villages requires not only infrastructure development but also continuous capacity building, operational support, and institutional strengthening. Integrating social capital such as community cooperation, local training initiatives, and tourism-based economic incentives can help reduce the performance gap and ensure the long-term sustainability of RE systems in community-based green tourism.

3.1 Human Resources Constraints and The Skill Gap

Based on the interview results with key persons in Desa Donoharjo, there was a lack of operators with capable skills to manage the renewable energy system. Some respondents mentioned the difficulties in reading the technical parameters, confusion in the maintenance effort, and the dependency on external parties. These conditions resulted in the maintenance delay, the incorrect diagnosis, prolonged downtime, and the decreasing of energy production efficiency. The dependency of the local community on the technician and the students (Sobi UGM) caused the operational bottleneck for the renewable energy implementation in this village.

This gap has created a mismatch of skills between the demands of modern renewable energy technology, which requires data analysis capabilities, system control knowledge, and rapid troubleshooting, and local training capacity that still focuses on manual labor. This results in energy losses and financial losses (such as increased electricity bills in Joglo), high maintenance costs, and the risk of system failure [11]. The findings in Desa Donoharjo reinforce the argument that the importance of local community capacity building and awareness of the significance of this project is equal to the availability of the technology itself. The implementation of solar panel energy is presented in **Table 2**.

Table 2. The solar panel energy implementation

Aspect	Existing Advantages	Identified Limitations	Proposed Resolution Strategies
Energy potential	Has potential solar energy to 1,101.2 kWh/m2	Has not been implemented due to broken converters and a broken accu.	Regular solar panel maintenance and operator training for local operators.
Daily Operation	The operation is fully conducted by the PIC of solar panels from the Sobi UGM team.	Strong dependence on the UGM team.	Introduce a multi-operator scheme and task rotation within the community.
Energy Production Monitoring	Operation requires complex technology for villagers.	No data on energy output or system efficiency.	Install basic monitoring tools and maintain manual or digital logbooks.
System Maintenance	Maintenance is done by PIC from Sobi UGM.	No regular monitoring Performance and system maintenance depend on the actions from the PIC of Sobi	Apply preventive maintenance routines and standardized inspection checklists and local operator training for villagers.

		UGM.	
Human Resources	No operator is coming from villagers. Operation mostly done by Sobi UGM.	Difficulties in transferring technical knowledge of solar panel procedures.	Implement tiered training programs and develop written operational documentation and appoint more persons to do the monitoring and maintenance.
Socioeconomic Context	Complaints from Joglo owner due to the increase in the electricity bill.	The installation plan did not involve all key representatives from the village, including the owner of Joglo.	Create a village renewable energy committee that controls and ensures the implementation of the renewable energy programs.
System Sustainability	External support from third parties is available	High dependence on external actors	Establish a local energy management institution at the village level.

3.2 The manual operations constraints and labor-intensive operations (case study in biodigester Desa Donoharjo)

The findings from the biodigester in Desa Donoharjo generally support previous empirical studies on community-scale biogas systems in rural areas and in donor-funded project contexts. Prior research consistently shows that the lack of systematic monitoring, performance records, and preventive maintenance can lead to efficiency losses of around 10–25% of total energy potential due to delayed fault detection and improper feeding practices [12]. The implementation of biodigester energy is presented in **Table 3**. The prolonged downtime observed in Desa Donoharjo, driven by dependence on a single operator, also aligns with studies demonstrating that labor centralization increases system vulnerability and operational disruption.

Table 3. The biodigester energy implementation

Aspect	Existing Advantages	Identified Limitations	Proposed Resolution Strategies
System infrastructure	Biodigester infrastructure is already installed and physical functional	Utilization is suboptimal with frequent downtime	Conduct periodic technical audits and implement a simple, schedule operational SOP
Feedstock Availability	Continuous and locally available animal waste	Energy potential has never been quantified	Estimate daily energy potential based on feedstock volume and record input data
Daily Operation	Manual operation is relatively easy to perform	Strong dependence on a single operator	Introduce a multi-operator scheme and task rotation within the community

Energy Production Monitoring	Operation does not require complex technology	No data on energy output or system efficiency	Install basic monitoring tools and maintain manual or digital logbooks
System Maintenance	Maintenance can be carried out using simple tools	Early-stage failures are not detected	Apply preventive maintenance routines and standardized inspection checklists
Human Resources	Operator has practical, hands-on experience	No knowledge transfer mechanism	Implement tiered training programs and develop written operational documentation
Socioeconomic Context	No social conflict due to free energy access	Low sense of community ownership	Develop non-financial incentive schemes
System Sustainability	External support from third parties is available	High dependence on external actors	Establish a local energy management institution at the village level

While some literature suggests that strong social cohesion can compensate for technical simplicity in small-scale renewable energy systems [13], the Desa Donoharjo case challenges this view. High social acceptance did not translate into shared operational responsibility or proactive management. Furthermore, evaluations of third-party-funded projects indicate that the absence of user contributions often weakens local ownership and accountability [14], underscoring that institutional and managerial factors, rather than technology alone, constrain biodigester performance and investment sustainability.

3.3 Renewable Energy as Strong Element Branding for Tourism Village

Although Desa Donoharjo has significant renewable energy assets together with the strong social modal, the technology optimalization not only improves the technical efficiency but also strengthens the position of this village as a tourism village. Based on a study done by Becken 2017, shows that low carbon destinations attract more tourists who care about the environment [15], so that the RE integration as part of educational tours, clean energy workshops as well as green energy usage for tourism facilities can strengthen the competitiveness of Desa Donoharjo energy education centres, and solar charging stations for outdoor activities. This integration not only enhances the tourist experience but also creates new jobs, such as energy tour guides and green technology education operators. Thus, optimal utilization of renewable energy not only closes the implementation gap but also transforms it into a key lever for tourism village development and strengthens Tanjung Village's narrative as a destination for sustainable and clean-energy tourism.

3.4 Solution Perspective

Based on the findings, automation in monitoring and control is an urgent need. Systems that can transmit real-time data, provide automatic alerts when anomalies occur, and provide performance dashboards will reduce reliance on daily manual inspections. Automation will result in: higher data accuracy, resulting in more informed maintenance decisions, predictive maintenance, enabling the identification of failures before they occur, efficient human resource allocation, as operators are less required to perform repetitive tasks such as meter readings or manual documentation, increased asset lifespan, as maintenance can be performed in a timely manner. Automation does not replace human labor but shifts their role from manual operators to intelligent system managers.

While automation reduces manual workload, local human resources still require new skills, such as basic data analysis, understanding solar power plant or biodigester performance indicators, operating digital control systems, and technical risk management. Training should focus on upskilling rather than simply reskilling, as modern renewable energy technologies require mastery of information, not just technical procedures. Decentralized renewable energy projects can ultimately only succeed if villages produce a local workforce capable of independently managing the new technology. Field findings indicate that the long-term sustainability of the system will be significantly influenced by the operators' ability to adopt new, knowledge-based roles.

4 Conclusion

This study shows that renewable energy systems in Desa Donoharjo, Sleman, Yogyakarta perform unevenly relative to their installed capacity despite adequate resource availability. Quantitative estimations using emission energy conversion, solar irradiation analysis, and the PSH approach indicate that solar PV operates close to its potential, while the biodigester shows a significant utilization gap. The results highlight that underperformance mainly system from operational management and limited local technical capacity rather than technological constraint.

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