G-Tech : Jurnal Teknologi Terapan
Vol. 10, No. 2, April 2026, p. 568-579
E-ISSN: 2623-064X | P-ISSN: 2580-8737

Integration of Renewable Energy in Water Management Systems in Remote Areas: A Systematic Review

Darwis Baso[1]✉

[1] Department of Environmental Engineering, Faculty of Engineering, Universitas Muslim Indonesia, Makassar, Indonesia

✉ **Corresponding Author :** Darwis Baso (e-mail: darwis.baso@umi.ac.id)

Article Information

Article History

Received : January 22, 2026
Revised : February 11, 2026
Published : April 02, 2026

***Keywords*:**

Micro Hydropower;
Remote Areas;
Renewable Energy Integration;
Water Management Systems

ABSTRACT

Limited access to energy and clean water services remains a major barrier to socio-economic development in remote areas, particularly in off-grid regions with very limited electricity infrastructure. This study presents a systematic review of renewable energy integration in water management systems, focusing on energy-water access challenges, technology characteristics, and conceptual suitability. A literature selection followed the PRISMA protocol for national and international journal articles published between 2021 and 2025. A total of 36 articles met the inclusion criteria, covering renewable energy technologies such as solar water pumping, micro-hydropower, small-scale wind systems, rainwater harvesting, and hybrid configurations. The findings indicate that decentralized water systems based on renewable energy especially solar pumping and micro-hydropower demonstrate the highest suitability due to good energy efficiency, low operation and maintenance costs, and minimal infrastructure requirements. Hybrid systems further enhance service reliability through energy source diversification and storage, although they involve greater system complexity. Implementation success is influenced not only by technical performance but also by institutional capacity, community skills, and social readiness. Overall, integrating renewable energy strengthens the energy-water nexus, expands access to basic services, and supports sustainable development in remote areas, with recommendations for field testing and further optimization of hybrid systems.

INTRODUCTION

Energy and clean water availability are interrelated basic needs that support sustainable development. Water management systems including abstraction, pumping, treatment, distribution, and sanitation require a reliable energy supply to operate optimally. In remote areas, limited access to main grid electricity (off-grid) often becomes a barrier to adequate water service provision (Cabello-Vargas et al., 2021). Dependence on fossil fuel-based energy sources such as diesel generators not only increases operational costs but also generates negative environmental impacts in the form of greenhouse gas emissions (Hassan et al., 2023). To address these challenges, integrating renewable energy into water management systems represents an important strategy to strengthen energy and water resilience in remote regions.

Renewable energy sources such as solar, wind, and micro-hydropower offer clean and locally available energy with the potential to reduce long-term operational costs (Afif et al., 2025; Hassan et al., 2023). In the context of water management, renewable energy technologies can be applied to pumping, treatment, and desalination processes (Solomon et al., 2021). Solar-powered water pumping systems have been implemented in various remote regions to pump water without reliance on main grid electricity or fossil fuels (Basem & Fard, 2024; Cruz et al., 2022). In Indonesia, solar-powered water pumps have also been used to support domestic needs and agricultural irrigation in remote areas (Akhiriyanto et al., 2025; Lase et al., 2022). Meanwhile, micro-hydropower technologies are utilized to supply energy for water services in rural communities (Afif et al., 2025; Hadi et al., 2025).

The integration of renewable energy into water systems has the potential to improve operational efficiency while enabling smarter and more sustainable water services. Literature shows that the use of renewable energy for water pumping, treatment, and distribution can reduce dependence on fossil energy and support more efficient energy management and monitoring (Ahmed et al., 2025; Bawayan et al., 2025). Systematic studies on isolated water and energy microgrids (IWEMGs) also highlight the importance of multi-technology integration to meet the water and energy needs of remote communities in a sustainable manner (Parraga et al., 2024; Sodomaco et al., 2025).

Despite its potential, the integration of renewable energy in water management systems faces both technical and social challenges. The variability of sources such as solar and wind can cause unstable energy supply without the support of storage systems or intelligent hybrid configurations (Samala & Bethi, 2025). In addition, community engagement, maintenance capacity, and upfront financing are key factors influencing implementation success. Recent research emphasizes the need for locally tailored operational models and technical training to ensure long-term sustainability (Ankel-Peters et al., 2025).

Based on this context, the present study aims to develop a conceptual review of renewable energy integration within water management systems in remote areas. This review focuses on identifying challenges related to limited access to energy and clean water services, analyzing system types and characteristics, and evaluating conceptual suitability under remote area conditions.

The research gap lies in the limited number of integrative approaches that link technical, spatial, and socio-economic dimensions in the application of renewable energy for water management systems in remote regions. Existing research is predominantly technical in focus, with insufficient assessment of service reliability and socio-economic sustainability. Explorations of multi-technology integration, such as solar gravity systems or small-scale solar desalination configurations, remain limited. Therefore, the hypothesis of this study is that context-appropriate renewable energy integration can improve water service reliability and overall system sustainability in remote areas.

RESEARCH METHODS

This study employs a systematic review approach to analyze the integration of renewable energy technologies within water management systems in remote areas. This approach was selected because the research does not focus on empirical testing or field experimentation, but rather on the examination of concepts, fundamental principles, and published scientific findings relevant to the research topic. Through this approach, a broader analytical space is obtained to evaluate technological suitability, integration potential, and implementation challenges within specific spatial and social contexts.

The research data sources were derived from scientific articles published in reputable national and international journals within the period of 2021 and 2025. The reviewed literature focuses on renewable energy technologies and water management systems in remote areas, encompassing technical, operational, and social dimensions. The literature search was conducted through scientific databases using a combination of keywords: “renewable energy” AND “remote areas” AND “water management” AND “off-grid system” AND “decentralized infrastructure”.

The literature selection process was conducted in accordance with the PRISMA (preferred reporting items for systematic reviews and meta-analyses) protocol, which includes the stages of identification, screening, eligibility assessment, and inclusion (Page et al., 2021). From the initial search, 219 articles were identified, of which 149 remained after duplicate removal. Subsequently, 74 articles were assessed as meeting the eligibility criteria, and through full-text review, 36 core articles were identified as directly relevant based on their publication year and research focus. All selection and exclusion procedures were systematically documented to ensure the transparency, validity, and reproducibility of the study (Figure 1).

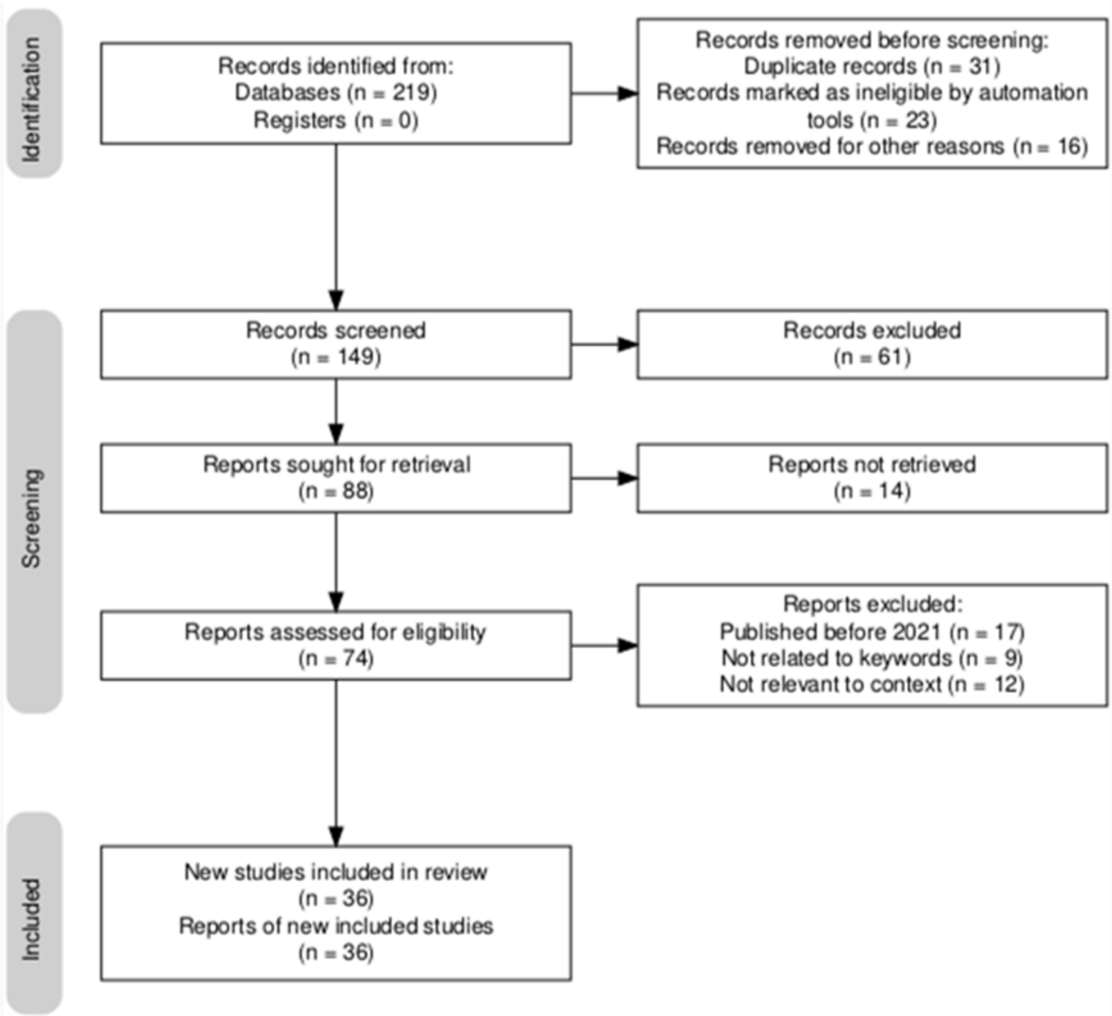

Figure 1. Systematic Review and Meta-Analysis Flow Diagram

The subsequent stages of the research were structured sequentially (Figure 2). Which include: (1) problem identification based on findings from previous studies; (2) categorization of the literature according to technology types, system characteristics, and suitability factors; and (3) qualitative analysis to identify patterns, relationships, and key findings across studies.

The technology suitability analysis was conducted using a Multi-Criteria Analysis (MCA) approach by integrating various criteria synthesized from the literature, including technical aspects, system type, energy sources, operation and maintenance, as well as suitability and performance. The technology assessment was based on the consistency of findings across studies, while considering the level of relevance of each criterion to the characteristics of remote areas. Furthermore, the level of technology suitability was determined through an aggregation process and subsequently analyzed comparatively as the basis for developing the results and discussion section.

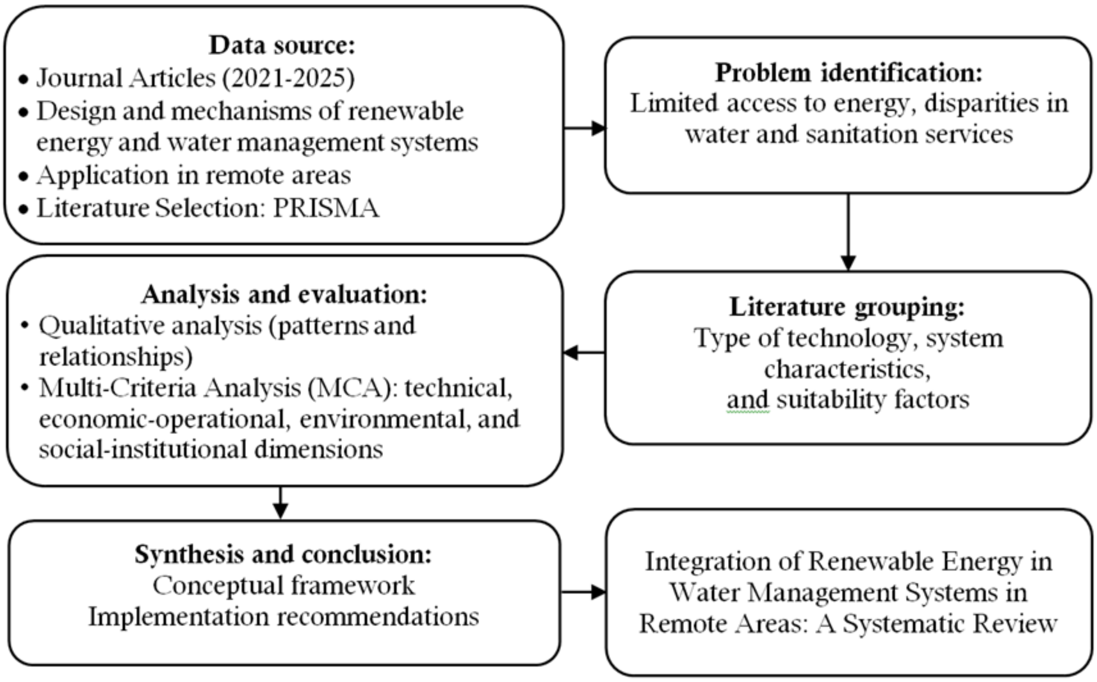

Figure 2. Research Method Diagram

RESULTS AND DISCUSSION

Identification of Issues Related to Limited Access to Energy and Clean Water Services

Remote areas in Indonesia continue to face limited access to energy and clean water services, which constitute a fundamental barrier to socio-economic development and improvements in public health. Although the national electrification program has made significant progress over the past two decades, disparities in access remain evident in rural and isolated regions. Government data indicate that the national electrification ratio reached approximately 99.83% by the end of 2024 (Statistik, 2025). However, there are still around 10,068 locations without electricity access, primarily in the 3T regions *(tertinggal, terdepan, dan terluar)*. This situation underscores that the provision of basic energy remains a strategic challenge, directly affecting the availability of clean water services.

Low energy access in rural areas affects household welfare because electricity is a prerequisite for the functioning of basic services, including drinking water and sanitation systems (Matimbwa & Mng'ong'o, 2024). A similar situation is observed in Indonesia, where the implementation of rural electrification policies still faces obstacles such as limited human resources, funding capacity, and interagency coordination, resulting in some communities not yet obtaining adequate energy access (Septian & Rahmadeni, 2024).

These energy constraints have a direct impact on clean water supply systems. Infrastructure such as pumping, distribution, and water treatment often fails to operate optimally due to unstable electricity supply or dependence on high-cost diesel generators. Evaluations of rural electrification programs indicate that approaches that are not pro-poor or insufficiently sensitive to local contexts may fail to reach the most vulnerable groups, thereby perpetuating clean water access issues (Cuenca-enrique & Acquila-natale, 2024).

In addition, disparities in drinking water access between urban and rural areas in Indonesia remain significant. Nationally, access to "improved" drinking water reaches approximately 93%, but the proportion of “safe” drinking water that meets quality standards is only 15.3% in urban areas and 8.3% in rural areas (Ekowati & Lusno, 2025). Several studies also report that access to improved water services in rural areas is only around 87%, compared to 96% in urban areas (Cabello-Vargas et al., 2021). This reflects a clear spatial disparity, particularly in remote and underdeveloped areas.

Beyond technical constraints, limited local capacity and financing constitute major barriers, particularly in remote communities that lack financial resources and the technical capability to operate and maintain systems without sustained external support (Basnet, 2024). Challenging geographic conditions such as small islands, mountainous areas, and remote forest regions increase infrastructure costs and reduce the efficiency of conventional systems, thereby underscoring the urgency of decentralized, self-sustaining technology-based approaches, including the use of renewable energy to support water management.

Overall, the combination of limited energy access, disparities in water and sanitation services, financing constraints, and challenging geographical conditions constitutes the root causes of basic service provision gaps in remote regions. Identifying these issues highlights the urgency of developing decentralized, self-sufficient, and sustainable service delivery solutions to close basic service gaps and promote inclusive development within remote communities.

Conceptual Framework and Operating Principles

The concept of integrating renewable energy into water management emphasizes the utilization of local, autonomous, and sustainable energy sources to support the entire water supply cycle, from abstraction to distribution. This approach is crucial in remote (off-grid) areas that require decentralized, flexible, and efficient systems. Renewable technologies particularly solar photovoltaic (PV) serve as substitutes for fossil-based energy due to their modular nature, which can be scaled for small- to medium-sized applications. PV systems convert solar radiation into electricity to power pumps and filtration units, enabling them to meet more than 80% of operational energy demand while reducing costs compared to traditional diesel generators (Alvarez et al., 2025).

Micro-hydropower is a critical option for remote areas with sufficient water flow and elevation. A turbine operating with a head of approximately 12 m and a flow rate of around 0.15 m^3/s can generate roughly 8 kW of electricity, which is adequate for clean water pumping and community lighting, and can operate continuously as long as water discharge remains stable (Syam, 2025). Bioenergy from biogas/biomass is also promising in regions with locally available organic waste, replacing fossil fuels for generators or boilers, supporting wastewater treatment processes, and reducing organic residues and emissions (Sari et al., 2023).

Systemically, renewable energy integration in water systems follows the energy-water nexus paradigm, emphasizing the interdependence between energy and water demands (Helerea et al., 2023). Conventional water services require substantial energy for abstraction, treatment, distribution, and wastewater processing (Zakariazadeh et al., 2024). Renewable energy provides lower operating costs and reduced emissions compared to fossil fuels, while enabling the deployment of sensor-based and intelligent management systems (Min et al., 2025). These smart water systems support real-time monitoring, demand-based energy optimization, and energy storage, ensuring operational reliability during periods of low energy availability, such as nighttime or dry seasons (Alvarez et al., 2025).

Overall, the operational principles of renewable energy in water management systems involve converting locally available natural resources into electrical or thermal energy, utilizing energy storage systems (e.g., batteries) to address variability, and integrating multiple technologies to ensure continuity and operational efficiency (Figure 3). This approach not only addresses energy challenges in remote areas but also supports environmental sustainability and long-term resilience of water services.

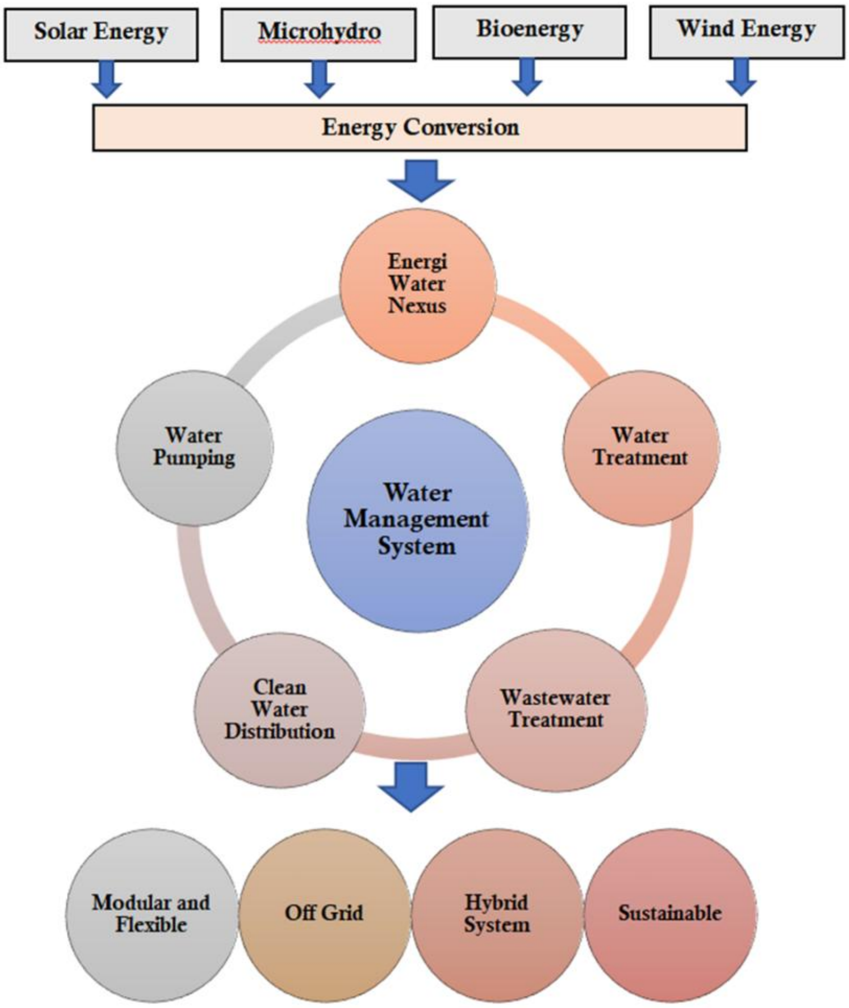

Figure 3. Integration of Renewable Energy in the Water Management System

Analysis of System Types and Characteristics

The analysis of renewable energy system types and characteristics for water management in remote areas focuses on the alignment of technological options with local resource potential, application needs, and environmental and socio-economic conditions. Since each technology has distinct technical performance, advantages, and limitations, solution selection must account for operational contexts in areas without access to grid electricity.

Solar photovoltaic (PV) energy is widely applied in off-grid water pumping and treatment systems, demonstrating technical and economic feasibility for rural communities and irrigation while reducing reliance on diesel generators (Solomon et al., 2021). PV systems are modular and adaptable for small-scale filtration and disinfection, though intermittent solar radiation often necessitates batteries or complementary energy sources. Micro-hydropower provides an efficient option in areas with continuous water flow, delivering stable power and competitive operating costs for pumps and control systems (A. Maulana & Wahab, 2025). Wind energy, particularly in hybrid wind-PV systems, enhances supply reliability for water pumping and lowers fossil fuel use (Bawayan et al., 2025). Biogas and biomass offer on-demand energy from organic waste, supporting water and wastewater treatment while reducing rural waste burdens.

Across the water management chain, renewable energy supports key stages: PV and micro-hydropower for pumping, PV, wind, or hybrid systems for filtration and disinfection, and biogas for wastewater treatment, particularly aeration. Context-specific technology selection and hybrid configurations based on local resource potential enhance the reliability and sustainability of water supply in areas with limited electricity access (Zakariazadeh et al., 2024). Accordingly, the integrated use of solar PV, micro-hydropower, wind, and biogas/biomass strengthens service continuity, reduces fossil energy dependence, and enables more autonomous and sustainable water management in remote regions (Hassan et al., 2023; Umam et al., 2024).

Table 1. Types and Characteristics of Renewable Energy Systems for Water Management

System Type	Energy Source	Applications	Key Advantages	Key Limitations	References
Solar PV	Solar radiation	Pumping, filtration, UV disinfection, small-scale desalination	Modular, easy installation, low O&M, off-grid suitable	Intermittent supply; requires battery or hybrid backup; weather-dependent	Solomon et al. (2021); Akhiriyanto et al. (2025)
Micro-Hydro power	Flowing water (potential & kinetic)	Continuous pumping, electricity for treatment and control units	24-hour operation, stable, battery-free, high efficiency	Requires minimum head & flow; location-limited	Maulana & Wahab (2025); Sinaga et al. (2025)
Wind Micro-Turbine	Wind kinetic energy	Mechanical/electric pumping in coastal and highland areas	Good for hybrid PV systems; long lifespan	Variable wind; needs control system	Bawayan et al. (2025); Parraga et al. (2024)
Biogas / Biomass	Organic waste	Heating, aeration, pumping, electricity generation for treatment	Uses local waste; on-demand; stable load	Requires sustainable feedstock; complex O&M	Zakariazadeh et al. (2024); Hamawand (2023)
Hybrid Systems	PV+Wind /Micro-Hydro/Bio gas	Pumping, filtration, desalination, monitoring and control	Improved reliability & continuity; reduced battery	Higher system and control complexity; careful design required	Hassan et al. (2023); Umam et al. (2024)

Table 1 summarizes the use of renewable energy sources for water management in remote areas based on their technical characteristics. Solar PV is effective for pumping, filtration, and small-scale desalination in tropical regions but requires storage or complementary sources due to intermittency (Akhiriyanto et al., 2025). Micro-hydropower offers continuous power for sustained pumping, though it is constrained by site-specific flow conditions (A. Maulana & Wahab, 2025). Wind micro-turbines enhance reliability in hybrid systems despite variability (Amri et al., 2025). Biogas/biomass provides on-demand energy from organic waste but requires feedstock and operational management (Bawayan et al., 2025). Hybrid PV-wind-micro hydropower systems optimize local resources and enhance reliability in off-grid villages. Therefore, a shift from centralized systems to decentralized approaches based on local potential is needed through resource-based planning and renewable energy mapping in remote areas.

Evaluation of Conceptual Suitability for Remote Area Conditions

The evaluation of renewable energy integration in remote water management systems shows strong technical, operational, and environmental relevance. Empirical evidence shows that renewable energy can provide reliable water supply without costly infrastructure. Off-grid solar pumping systems are effective for irrigation and domestic needs with low energy consumption and competitive costs, and are suitable for shallow wells and small-scale distribution (Akhiriyanto et al., 2025). Case studies further confirm that solar pumping is a technically and economically viable alternative to grid extension or diesel generators in remote regions (Hasibuan & Barisqy, 2023).

Micro-hydropower technology also demonstrates a high level of suitability for remote areas because it utilizes local water resources and is capable of providing continuous energy. An analysis of the flow potential of the Wira Garden River shows that with a discharge of approximately 4.2 m^3/s and a head of ±2 m, the potential electrical power output reaches around 74.2 kW, offering the possibility of meeting community energy needs and supporting the operation of electricity-based systems at the local level (Rosmalia et al., 2025). This study reinforces that micro-hydro represents a reliable and sustainable renewable energy option, particularly in regions with stable hydrological potential.

From an operational and economic standpoint, renewable energy enhances water service continuity with lower O&M costs than fossil-based systems. Hybrid configurations often achieve ≥80% renewable energy fractions, reduce fuel use, and lower LCOE compared to diesel-only systems (R. Maulana, 2024). By reducing solar and wind variability to eliminate diesel backup, renewable energy integration is well suited for remote water management as it provides reliable, low-impact services, with long-term sustainability depending on local adaptation, hybrid design, community capacity, and institutional support.

Table 2. Suitability and Performance of Water Supply Systems for Remote Areas

System	Energy Source	O&M	Suitability	Performance	Reference
Gravity	≈0 electricity	Low	Highly suitable	High performance if topography supports; no electricity; suitable for hills/mountains	Nurfajriah et al. (2021); Sari et al. (2023)
Solar Pumping (PV)	PV-dependent	Low-Medium	Highly suitable /Suitable with limitations	High performance with adequate solar radiation; suitable off-grid	Hasibuan & Barisqy (2023); Ouedraogo et al. (2025); Akhiriyanto et al. (2025)
Micro-Hydro	Turbine electricity	Medium	Highly suitable	Stable performance if flov consistent; electricity fror local stream	Rumbayan & Rumbayan (2023); Rosmalia et al. (2025)
Wind Pumping (Micro)	Wind-dependent	Medium	Suitable with limitations	Variable performance; often hybrid; requires adequate wind	Quipo et al. (2024); Bawayan et al. (2025);
RWH + Filtration	Low	Low-Medium	Suitable with limitations	Performance depends on rainfall; alternative in rainy season	Dirgawati et al.(2024)
RO Desalination (RES)	High	Medium-High	Unsuitable / Expensive	High performance if seawater source available RES integration improve performance	Zakariazadeh et al.(2024)
Hybrid HRES (Pumping)	Mix-dependent	Medium	Highly suitable Suitable with limitations	High performance if properly designed; hybric PV, other sources	Basem & Fard (2024); Maulana (2024)

In Table 2, gravity-fed systems emerge as one of the most suitable options for remote areas when topography allows, as they provide water without electricity, require minimal external infrastructure, and have low operation and maintenance (O&M) costs. This system is highly effective in hilly and mountainous regions (Nurfajriah et al., 2021; Sari et al., 2023). Photovoltaic (PV)-based solar pumping systems deliver high water supply performance in areas with sufficient solar radiation, do not require grid electricity, and have relatively low O&M complexity. Although initial and O&M costs are moderate, PV systems are categorized as "highly suitable" or "suitable with limitations," making them ideal for off-grid applications, especially shallow wells and small-scale distribution (Ouedraogo et al., 2025).

Micro-hydro systems provide stable year-round water supply, generating electricity for pumps or treatment units with low infrastructure dependency and medium O&M costs, operating 24/7 without fossil fuels in regions with stable hydrological potential (Rumbayan & Rumbayan, 2023). Micro wind pumping systems show more variable water supply due to local wind fluctuations. With medium O&M complexity and low infrastructure dependency, these systems are considered "suitable with limitations." In practice, wind systems are often integrated with PV or batteries in hybrid configurations to enhance reliability, serving as a renewable pumping option for remote areas with adequate wind resources (Ahmed et al., 2025; Bawayan et al., 2025; Quipo et al., 2024).

Decentralized water systems based on renewable energy (gravity-driven systems, solar pumping, and micro-hydropower) are the most suitable for remote areas due to their energy efficiency, low O&M costs, and minimal infrastructure requirements. Consequently, policies need to shift from centralized approaches toward locally contextualized planning, while fossil fuel based systems demonstrate low feasibility. The integration of renewable energy strengthens the energy water nexus resilience and the long-term sustainability of water services in remote regions.

Future research should focus on field implementation of integrated renewable energy systems, community acceptance, and institutional capacity. While also exploring hybrid designs, smart management, and financing models to improve efficiency, scalability, and theoretical contributions to the energy water nexus in remote regions.

CONCLUSION

The results of this study confirm that limited access to energy and clean water remains a major constraint on socio-economic development in remote regions of Indonesia, particularly in underdeveloped, frontier, and outermost 3T regions *(tertinggal, terdepan, dan terluar)*. The analysis indicates that renewable energy technologies, particularly solar photovoltaic systems and micro-hydropower, have the highest suitability for autonomous and sustainable water supply. This is supported by high energy efficiency, low operation and maintenance costs, and minimal infrastructure requirements. Hybrid systems further enhance reliability through the diversification of energy sources. This study emphasizes that successful implementation is determined not only by technical aspects but also by institutional capacity, community operational skills, and social readiness. Furthermore, it highlights the need for a policy shift toward decentralized planning based on local context, supported by institutional strengthening and community capacity building to ensure the sustainability of water services in remote areas.

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