Potential of Micro Hydro Power in Sabah and Sarawak: A Techno-Economic Assessment and Regional Sustainability Review

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ABSTRACT

This paper evaluates the potential of micro-hydropower (MHP) systems as a sustainable and reliable solution for rural electricity supply in Sabah and Sarawak, Malaysia, by utilising the region's favourable hydrological and topographical characteristics. Despite the continuous development of national electricity infrastructure, many remote communities in East Malaysia remain without reliable access to electricity due to geographical constraints, challenging terrain and the high capital costs associated with grid extension. Given the extensive river networks and significant water resources available in Sabah and Sarawak, MHP systems present a promising alternative for decentralised electricity generation and rural electrification. This study highlights the technical advantages of MHP compared with other renewable energy sources, particularly its capability to provide a continuous and relatively stable electricity supply throughout the day, provided that sufficient water flow is maintained. Unlike solar photovoltaic and wind energy systems, which are highly dependent on weather conditions and environmental variations, MHP systems can offer more consistent power generation. Furthermore, the economic feasibility of MHP is discussed in terms of its relatively low operational and maintenance requirements, potential long-term cost savings and reduced dependence on diesel generators and other fossil-fuel-based electricity sources. The implementation of MHP systems could also contribute to improving energy accessibility, supporting rural socioeconomic development and reducing carbon emissions. Overall, this paper emphasises the importance of harnessing locally available water resources to establish reliable, affordable and environmentally sustainable electricity solutions for remote communities in Sabah and Sarawak, while supporting Malaysia's broader renewable energy transition and national carbon reduction targets. To rigorously substantiate this potential, this study incorporates a quantitative hydraulic power assessment ($P = \rho g Q H \eta$) across three representative rural sites (Long Lawen, Buayan Ulu Papar, and Long Peluan), yielding estimated capacities between 9.1 kW and 14.1 kW to meet community baseload demands. A comparative economic assessment demonstrates an LCOE of USD 0.08 to 0.18/kWh for micro-hydro versus USD 0.16 to 0.28/kWh for solar PV-battery systems and USD 0.35 to 0.70/kWh for off-grid diesel generation. Furthermore, a transparent evaluation of Sarawak's historical 12 of 27 operating units identifies technical, environmental, and governance failure mechanisms alongside mitigation recommendations

Keywords: Micro-hydropower, Renewable Energy, Greenhouse, Fossil Fuel, Levelised Cost of Electricity, Rural Electrification, Sabah and Sarawak

INTRODUCTION TO MICRO HYDRO POWER

Micro-hydro power is increasingly recognized as a vital renewable energy option in Malaysia, especially for rural and remote areas in Sabah and Sarawak where grid access remains limited. National efforts to expand renewable energy have highlighted hydropower as a dependable and low-emission source that aligns well with Malaysia's sustainability targets [1]. In East Malaysia, the natural environment characterized by heavy rainfall, steep terrain, and numerous river systems creates ideal conditions for the development of micro-hydropower, particularly in underserved communities that continue to experience energy poverty [2].

Research in Sarawak shows that integrating local renewable energy resources can significantly enhance rural electrification, with micro-hydropower standing out as a practical and community-focused solution [3]. Broader assessments of Malaysia's renewable energy technologies further confirm that micro-hydro systems offer strong potential due to their scalability, reliability, and suitability for rural settings [4]. This is supported by successful implementations such as the micro-hydro mini-grid projects in Ulu Papar, which have improved off-grid electricity access and supported agricultural and community-based economic activities [5].

Community participation is a key factor influencing the sustainability of micro-hydropower initiatives in Sabah and Sarawak. Community-led programs that emphasize capacity building, local management, and shared responsibility have proven effective in addressing rural infrastructure challenges [6]. In Sabah, projects like gravity-flow water systems under the APPGM-SDG initiative demonstrate how community empowerment can protect the environment while improving the quality of life in rural settlements [7]. At the same time, past rural electrification projects in Malaysian Borneo show that long-term success depends greatly on user perceptions, community ownership, and continued technical support, emphasizing the need for strong socio-technical cooperation [8].

Overall, micro-hydropower offers a promising pathway for sustainable, community driven electrification in Sabah and Sarawak, with strong potential to reduce energy inequality while supporting environmental conservation and rural development. Despite national electrification rates exceeding 99% in Peninsular Malaysia, approximately 15,000 to 20,000 rural and indigenous households across the interior highlands of Sabah and Sarawak still lack reliable 24-hour electricity access [3, 8]. Most unconnected villages rely on standalone diesel generators operated for only 4 to 6 hours nightly due to extreme fuel logistics costs (RM 3.50 to 5.50/L after river and 4WD transport). This substantial energy gap underscores the pressing need for a systematic, site-specific evaluation of indigenous micro-hydro resources [3, 5].

Quantitative Power Potential Assessment and Modelling: Mathematical Formulation of Hydraulic Potential

The available theoretical and electrical power output (P, in Watts) of a run-of-river micro-hydro installation is modelled using standard fluid mechanics principles as in Equ (1):

$$P = \rho g Q H_{net} \eta_{total} \quad (1)$$

Where ρ is the density of fresh water (1000 kg/m³), g is acceleration due to gravity (9.81 m/s²), Q is the design discharge flow rate (m³/s) selected at 90% exceedance flow from stream flow-duration curves to account for dry season baseflow, H_net is the effective net head (m) after subtracting frictional penstock head losses, and η_total is the combined system efficiency (typically 0.55 to 0.65 for rural crossflow or Pelton turbines, generators, and electronic load controllers) [5, 11, 12]. Table 1 shows the quantitative hydraulic and electrical output for selected sides in Sabah and Sarawak, namely as Long Lawen, Belaga (Sarawak), Buayan, Ulu Papar (Sabah) and Long Peluan, Baram (Sarawak). Here, several parameters have been highlighted such vet head, design flow, efficiency and calculated power.

Table 1: Quantitative Hydraulic and Electrical Output for Selected Sites in Sabah and Sarawak

Site Name & Location	Net Head (H_net)	Design Flow (Q)	Efficiency (η)	Calculated Power (P)	Village Demand Served
Long Lawen, Belaga (Sarawak)	12.5 m	0.12 m³/s	0.62 (Crossflow)	9.1 kW	68 households; domestic lighting, refrigeration, schooling [11]
Buayan, Ulu Papar (Sabah)	31.0 m	0.06 m³/s	0.65 (Pelton/Turgo)	11.9 kW	45 households; micro-enterprise, rice milling, lighting [5]

Long Peluan, Baram (Sarawak)	16.0 m	0.15 m³/s	0.60 (Crossflow)	14.1 kW	80 households; community clinic cold-chain, lighting [3]

Advantage of Micro Hydro Power

Capable of Micro Hydro Power

Micro hydro power plants are one of the best technologies for generating energy from renewable sources other than solar panels and wind turbines that can be applied at Sabah and Sarawak. This is because of the waterwheel design works 24 hours a day, seven days a week, unlike solar panels which is require the sun's light all the time and wind turbines which require at the very least a strong breeze [6]. Since Sabah and Sarawak have low to moderate breeze speeds and always cloudy because being located at equatorial plane this make micro hydro power plant the most suitable technologies to being develop in those states.

Other than this, the continuous 24/7 operation is contingent on perennial river flow; during prolonged dry seasons, run-of-river discharge drops significantly, requiring conservative low-flow sizing or hybrid battery backup [11, 13]. Furthermore, while frequent equatorial cloud cover attenuates peak solar irradiance, regional daily solar irradiation remains viable at 4.2–5.0 kWh/m²/day, meaning solar PV is not unviable but rather complementary to hydro baseflow [11, 13].

Reduces Greenhouse Gas Emissions

As we know, fossil fuels are major contributors to carbon emissions, which drive global warming and climate change. As Malaysia going to achieve their goals on net zero emission by 2050, micro hydro power is one of the best options since its reliance on fossil fuels are so low that can result in reducing greenhouse gas emissions [1]. Although it's not 100 percent free emission it's still bet technologies that make us to achieve our goals.

Decentralized Energy Production

One of the primary advantages of micro hydro power is its ability to provide decentralized energy production [3]. Unlike large hydroelectric project that need extensive transmission infrastructure to deliver electricity over long distances, micro hydro power plants can be located closer to end-users. This eventually will reduce transmission losses and enhance energy security by creating more localized energy sources. Lower transmission losses lead to increased overall efficiency and reduced expenses for consumers.

Cost Effective

Micro hydro power can be considered as a cost- effective energy solution [4]. To build a small-scale hydro-power system costs around $1,000 to $20,000, depending on site and terrain in Sabah and Sarawak since most of its rural and forested area. Maintenance fees are relatively low in comparison with other renewable technologies. Moreover, hydro power is a durable and robust technology that can last for 50 years or more without any major new investments [4]. The $ 1,000 $ 20,000 figure represents rudimentary pico-hydro units (<5 kW) built with locally fabricated components and community labor. In contrast, engineered community-scale micro-hydro systems (10 – 50 kW) require capital expenditures of USD 3,000 to 6,500 per kW due to substantial civil works (intake weirs, desilting basins, and penstock transit over rugged terrain). Nonetheless, because operating costs are minimal (USD 0 fuel), micro-hydro achieves the lowest lifecycle Levelised Cost of Electricity (USD 0.08–0.18/kWh) over 25–40 years as shown in Table 2 [9, 10].

Challenge of Micro Hydro Power

Several issues and challenges continue to hinder the growth of small hydropower in Sabah and Sarawak. The most significant barrier is the shortage of field experts and technical skills, while financial institutions also lack experience in evaluating risks associated with small hydropower projects. Malaysia further faces specific obstacles such as heavy rainfall that leads to flooding and overflow, ineffective systems for filtering sand and

debris before they reach the turbine, complex regulatory procedures involving land acquisition and environmental impact assessments, and potential water pollution during construction due to logging activities [1]. Additionally, access to land and water is governed by both federal and state regulations.

In 2016, the global potential for small hydropower was estimated at 217 GW, with about 78 GW already installed an increase of 4% since 2013. This 78 GW accounted for roughly 7% of the world's total renewable energy generation in that year [14]. At the same time, global solar power capacity continued to grow rapidly, reaching 227 GW in 2015, which is ten times greater than the cumulative capacity recorded only ten years earlier [15]. More recent figures from IRENA (2023) show global small hydropower capacity reaching 140 GW and cumulative solar PV exceeding 1,050 GW by 2022, underscoring both mature hydro deployment and accelerating decentralized solar growth [9, 10]. Given these trends, Local Electrical Authority (LEA)'s decision to adopt micro- hydropower and solar energy for rural electrification in Sarawak is appropriate, as both technologies are widely recognized and increasingly utilized as sustainable solutions around the world.

In the context of Sarawak, the use of micro-hydro systems has not yet been fully maximized. Micro Hydroelectric Power (MHEP) systems are generally more cost-efficient, require less maintenance, and offer a longer operational lifespan compared to Solar Energy Systems (SES) [11]. This is evident as 12 out of the 27 installed MHEP units have been functioning for more than five years, and the system at Long Lawen has reliably generated electricity since 2002. At present, only one hybrid Micro Hydroelectric Power with Photovoltaic (MHEP-PV) system exists in Kpg. Keranggas, but it has been reported to be non-operational since 2011. Nevertheless, micro- hydro systems are not simple plug-and-play solutions; each site has distinct characteristics that demand thorough planning, design, and implementation to ensure successful operation. Crucially, that only 12 out of 27 units remained operational indicates a 55.6% failure and abandonment rate. Rather than demonstrating uncompromised reliability, this track record exposes major sustainability vulnerabilities:

(1) severe intake sedimentation and runner abrasion from upstream commercial logging,

(2) lack of trained village operators and local supply chains for electronic load controller and governor repairs,

(3) migration of community youth to urban centers, and

(4) the state utility's subsequent shift toward centralized solar micro-grids under the Sarawak Alternative Rural Electrification Scheme (SARES) [3, 8, 11].

Run-of-river installations in streams with less than 10 m static head require substantial volumetric flow rates and large-diameter crossflow or Kaplan turbines, which exponentially inflate civil excavation and piping costs, rendering low-head sites uneconomical for small remote villages [11]. Additionally, setting up an MHEP typically involves costly civil works and control systems. However, these expenses can be reduced by engaging the local community in construction activities and using locally produced components [6]. Maintenance costs can likewise be minimized by training residents and conducting periodic inspections by the Local Electrical Authority (LEA) or an appointed agency. Moreover, as noted by the Jaringan Orang Asal SeMalaysia (JOAS) team leader, strong leadership and a well-organized community are crucial factors for the successful implementation of an MHEP project [16].

Hydrological parameters also play a crucial role in determining the success of small hydropower projects. Run-of-river schemes share a common limitation: water availability fluctuates across seasons. Assessing the feasibility of small hydro projects is challenging due to risks such as water scarcity and unpredictable flows caused by dry seasons, climate change, and river pollution. In addition, the performance of small hydropower systems is affected by sedimentation, which decreases overall generating efficiency [17]. Therefore, more detailed research is needed on sedimentation, including ways to address sediment- related issues and improve sediment management in small hydro systems.

Installation and infrastructure costs can also be high, especially when developing canals, pipelines, or access routes in remote areas. Maintenance is another challenge, as debris, sedimentation, and floods can damage turbines or block water intakes, requiring skilled labor for repairs. Lastly, micro-hydro systems can create

ecological impacts if not designed carefully, such as disrupting aquatic habitats or altering natural water flow. These challenges highlight the need for proper site assessment, community training, and environmentally conscious engineering to ensure the system operates effectively over time.

Possibilities in Applying Micro-Hydropower as Main Source of Power

Geographical Features

The micro hydropower can provide clean generation of energy, even in rivers or streams with low water retention and flow [5]. This is highly relevant to Sabah and Sarawak, where the terrain is mountainous and hilly, resulting in fast flowing rivers making their geomorphological conditions particularly favorable for micro hydropower to be utilized effectively. High annual rainfall and dense river across both states ensure consistent water availability and since micro hydropower relies on flowing water, it provides a stable and continuous energy supply as long as the water source remains available [1]. To highlight, Sabah and Sarawak have a suitable geographical feature and weather that can ensure the effectiveness of this system.

Economic Feasibility

The micro hydro power is not only technically viable but also economically viable for improving states like Sabah and Sarawak. This system has minimal startup costs, and it offers a quicker return on investment than wind or solar energy, due to its higher capacity factor (utilization) [10]. Operating and maintenance costs are minimal, and the renewable energy resource potential for small hydropower in Malaysia was projected to generate electricity value exceeding RM 506 million annually based on national river basin assessments [1]. This system is cheap and pollution free, allowing hour significant environmental impact while preserving local flora and ecosystem. Collectively, these factors demonstrate that micro hydropower is a cost- effective solution for sustaining electricity in Sabah and Sarawak [3, 5].

Distributed micro hydropower generation

Malaysia, with 150 river systems in Peninsular Malaysia and over 50 major river basins across Sabah and Sarawak, is blessed with an abundance of water resources [1]. The micro hydropower generation can be distributed to multiple generators in multiple sites, enhancing energy reliability, reducing transmission losses, and minimizing the risk of total system failure if one site encounters operational issues. All individuals and communities in Sabah and Sarawak can gain access to the renewable energy generated through strategically placed micro hydro units [3, 5]. By placing these small-scale systems across rivers and streams near villages, electricity can be delivered locally, reducing dependence on the centralized grid and long-distance transmission. These characteristics show that this system can provide energy to remote corners in Sabah and Sarawak consistently.

Growths of Micro-Hydropower as Main Source of Power

Integration IoT System Monitoring

The growth of micro-hydropower in Sabah and Sarawak reflects the increasing need for renewable and reliable electricity for rural communities, like the concept presented in the “Future Micro Hydro Power” system, which demonstrates how energy can be produced efficiently from small water sources and monitored through IoT [18]. As both states contain vast river networks and hilly terrains, their geographical conditions make micro-hydro a practical solution to reduce dependence on public grids and overcome frequent load shedding.

Like modern remote-monitoring systems, where turbines generate energy from continuous water flow and transmit operational data [18], many rural villages in East Malaysia could benefit from small-scale hydro systems that provide stable, low-cost, and environmentally friendly electricity. In addition to that, taking rural areas of Sabah and Sarawak into account, this could serve as an additional water level monitoring to prevent any accident such as flash flood or in case of theft of the technology.

Topographical Suitability of the East Malaysia Landscape

Sabah and Sarawak are experiencing increasing interest in micro-hydropower projects in response to rural electrification challenges. This explains how micro-hydro technology is cost-effective, portable, reliable, and environmentally friendly qualities that suit remote East Malaysian settlements where access to the national grid remains limited [5, 11]. The principles such as generating electricity using fast running water, recycling the water source, and producing consistent power even with modest flow rates, represent the same engineering approach used in rural micro-hydro initiatives across Borneo [5]. Since the landscape really help in proving this system could work this also means that there are many places for the micro-hydro system to be installed here. As the efficiency and simplicity of these systems continue to improve, Sabah and Sarawak are poised to accelerate their adoption of small-scale hydro solutions, strengthening energy stability while reducing greenhouse gas emissions and reliance on diesel generators even though there are some loses in energy efficiency compared to diesel, it could be substitute as an emergency or additional power system.

Hybrid Renewable System

The growing adoption of micro-hydropower among consumers is further strengthened by hybrid renewable energy models that integrate micro-hydro with solar power to provide continuous and reliable electricity [13]. The study shows that individual renewable sources such as solar or micro-hydro may face limitations due to seasonal and daily variations, but when combined, they create a more balanced and stable energy system capable of supplying consistent household power. Simulation results produced using HOMER demonstrate that micro-hydro can reliably support a significant portion of the base electrical load, ensuring uninterrupted energy access throughout the day [13]. By incorporating photovoltaic panels alongside a micro-hydropower unit and a backup generator, the hybrid system significantly reduces diesel consumption and lowers long-term energy costs for consumers [13]. This approach showcases how micro-hydropower can serve as a dependable and cost-efficient component of a broader renewable energy strategy, empowering consumers with sustainable and resilient electricity solutions.

DISCUSSION AND LIMITATIONS

The quantitative evaluation across Long Lawen, Buayan, and Long Peluan confirms that micro-hydropower can reliably deliver 9.1 to 14.1 kW of baseload electricity at an LCOE of USD 0.08–0.18/kWh, undercutting diesel by over 60%. However, long-term sustainability hinges on addressing the 55.6% failure rate recorded in earlier Sarawak schemes. Technical success is inseparable from watershed preservation: without legal protection against catchment logging, siltation will continue to render civil intakes inoperative. Furthermore, hybridizing micro-hydro with solar PV and minimal battery storage provides the most resilient configuration to counter equatorial dry-season flow drops [3, 11, 13].

This study's primary limitation is the scarcity of long-term, continuous river gauging telemetry across remote headwater catchments in Sabah and Sarawak. Flow estimates frequently rely on short-term empirical flow measurements or community recollections, which increases hydrological uncertainty during extreme drought periods. Long-term hydrological monitoring stations are required to generate robust flow-duration curves for future schemes [5, 11].

Policy and Engineering Requirements

Based on regional findings, three key measures are recommended:

(1) Statutory Catchment Gazetting: State forestry departments and natural resource agencies must legally gazette village micro-hydro catchments to halt upstream commercial logging and oil palm expansion;

(2) Institutional Operator Training: SEDA, Sarawak Energy, and SESB should establish accredited technical training for village youth, covering intake desilting, runner maintenance, and electronic load controller diagnostics; and

(3) Hybrid Tender Guidelines: Rural electrification programs such as SARES and BELB should systematically prioritize hydro-solar hybrid micro-grids over standalone single-source systems to ensure 24/7 reliability across all seasons [1, 3, 8].

CONCLUSION

Micro-hydropower represents an indispensable, low-emission baseload generation asset for remote rural communities in Sabah and Sarawak where grid extension remains economically prohibitive. When sited at natural heads above 10 meters and designed to conservative dry-season exceedance flows (Q90), micro-hydro provides the most cost-effective long-term electricity supply (LCOE USD 0.08–0.18/kWh). However, realizing this potential requires moving beyond technology demonstration to robust watershed management, local technical capacity building, and hybridization with solar PV to secure sustainable rural energy access.

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