

Strengthening Micro-hydro Initiatives for Community-Based Sustainable Forest Management

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ABSTRACT

Limited access to clean, reliable energy remains a major challenge for forest-dependent communities across many developing regions. At the same time, ongoing forest degradation and climate pressures threaten watershed function vital to community resilience. This study examines the role of Micro Hydro Power Plants (MHPPs) as an incentive-based instrument within the Community-Based Sustainable Forest Management (CBSFM) framework. Using an inductive method, data from 14 MHPP sites were analyzed to identify key success factors and barriers. Each site was characterized by construction year, capacity, user numbers, participation level, stakeholder involvement, financing, and existing conditions. The findings highlight that success depends on active community participation, implementation of Payment for Watershed Ecosystem Services (PWES) scheme, and perpetual motion approach, which foster self-sustaining progress through community motivation and local resource mobilization. Despite limited quantitative data, qualitative insights show that MHPP contributes to rural economic growth, forest conservation, and stronger community awareness of collective forest protection.

Keywords

Renewable energy;
Forest communities;
Participatory governance;
Institutional capacity;
Hydrological data

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1. Introduction

Forests sustain ecological balance and biodiversity, mitigate climate change, and regulate the global hydrological cycle by controlling water quantity, quality, and distribution. Forested watersheds supply 75% of the world's freshwater to over half of the global population [1]. Sustaining forest ecosystem function is therefore critical to securing water availability, community welfare, and energy security. Yet, many remote forest-edge, such as those in Indonesia [2-4], Nigeria [5], Cameroon [6], the Amazon region (Peru, Brazil, Ecuador, and Colombia) [7-9], Argentina, Mexico [10], and Iran [11], still lack reliable access of energy, while ongoing forest degradation further undermines ecosystem services. This convergence of limited energy access and declining

forest integrity highlights the need for integrated upstream solutions that simultaneously enhance energy access and promote forest conservation.

In Indonesia, around 25,863 villages accommodate over 9.2 million households, located in or adjacent to forested areas. Notably, more than one-third of the inhabitants in these areas live below the poverty threshold [12]. The community's dependence on forest resources for their livelihoods often results in forest overexploitation and degradation. The government of Indonesia has launched the Community-Based Sustainable Forest Management (CBSFM) Program to empower forest-edge communities to manage forest resources sustainably while improving their livelihood. This program ultimately aims to safeguard water, food, and energy resources.

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One practical and context-appropriate solution is the development of micro-hydro power plants (MHPPs). These small-scale, renewable systems, typically under 1 MW [13], provide clean, affordable electricity with minimal environmental disruption [14, 15]. Micro hydro is the second top-ranked energy source for sustainable electricity generation in Indonesia after solar energy [16]. Micro-hydro produces electricity without the need for large dams, making it a typically sustainable option with low environmental impact [15]. MHPPs are particularly effective in remote, off-grid areas, offering energy for both household consumption and productive uses. They not only reduce greenhouse gas emissions but also stimulate local economies, improve public services such as health and education, and decrease dependency on forest exploitation for energy needs [15, 17]. MHPPs offer technical and economic benefits while supporting sustainable forest management. By following CBSFM principles, micro-hydro initiatives act as energy access solutions and conservation motivators, while also enhancing socio-institutional structures for managing natural resources.

Although the MHPP approach shows strong potential, there is no clear data yet identifying which forest-adjacent villages in Indonesia are suitable for MHPP development to support the success of CBSFM. However, using the approach proposed by Setiawan [18], suitable sites can be estimated based on topographic conditions, rainfall, and supporting factors such as proximity to roads and settlements. A conservative estimate, based on resource availability, terrain conditions, and practical lessons from government and pilot MHPP projects, indicates that only 10–30% of the 25,863 forest-adjacent villages (about 2,500–7,800) are realistically suitable for MHPP development, given technical, environmental, and socio-economic constraints.

Despite their potential, MHPPs implementation in Indonesia has produced mixed results. Although supported by national and regional government budgets, as well as donors funds, many projects have failed due to technical and non-technical reasons, including those in Sumbawa, West Nusa Tenggara [19], Semarang, Central Java [20], Kapuas Hulu, West Kalimantan [21], Sorong, West Papua [22], and Sinjai [23] and East Luwu in South Sulawesi [24]. The failures stem from fund misallocation and corruption, weak community engagement throughout the project cycle, and the externally imposed technologies that often mismatch local conditions and limit technology transfer [22]. Technical barriers further

constrain performance, including site-specific optimization challenges, reliance on skilled technicians for installation, and continuous maintenance [25], infrastructure limitations, high upfront expenses [26], grid integration difficulties, limited access to remote areas [27], and complex regulatory and permitting processes across jurisdictions [28].

To address existing gaps and inform future interventions, this paper draws on accumulated evidence from 468 micro-hydropower (MHP) publications in Indonesia (2000–2025), identified through the Publish or Perish application, which shows that most studies rely on single-site case analyses and rarely apply comparative approach integrating hydrological, governance, socio-institutional, and financial dimensions. As a result, findings remain fragmented and difficult to generalize for policy development or scaling.

This study synthesizes evidence from multiple community-based MHPP initiatives in Indonesia's forest margins to generate transferable insights for policy and scaling. Specifically, it aims to: (1) evaluate the implementation performance of community-based MHPPs under CBSFM; (2) identify key technical, socio-institutional, financial, and environmental determinants shaping long-term sustainability; and (3) develop an integrated incentive-based Payment for Watershed Ecosystem Services (PWES) model to strengthen the water–energy–forest nexus and enable scalable micro-hydro development in forest-adjacent communities.

2. Materials and Methods

This research employs an inductive method by identifying key factors essential for developing participatory Micro Hydro Power Plants (MHPP). In contrast to deductive methods that begin with established theories and hypotheses, this study applies an inductive approach that develops insights directly from raw data, allowing patterns, themes, and key technical, social, economic, and institutional factors influencing MHPP success to naturally emerge [29, 30].

2.1. Study Framework

The study framework in Figure 1 illustrates the research stages and key factors influencing community-based micro-hydro power development and productive energy use. The study was conducted through three steps: (a) data collection from existing MHPPs, (b) project characterization, and (c) data analysis and synthesis.

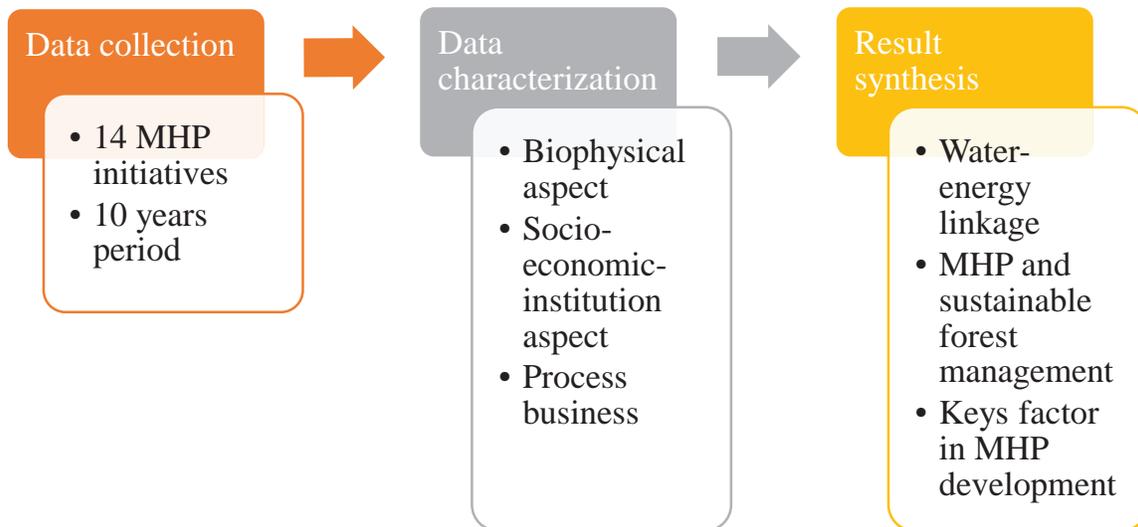


Figure 1: The study framework.

A descriptive analysis approach was used to interpret data from field observations, interviews, and secondary sources, identifying key patterns and relationships in technical performance, institutional arrangements, and community participation in MHP development. This method provides an in-depth understanding of site-site conditions influencing project sustainability without applying complex statistical techniques.

2.2. Data Collection and Characterization

This study analyses data from 14 community-based micro-hydro power projects (MHPPs) implemented between 2009 and 2019, in which the authors were directly involved as researchers. These projects were conducted in forest-adjacent villages across Sulawesi, Kalimantan, and East Nusa Tenggara (Figure 2), with support from National Parks, conservation agencies, provincial forestry offices, NGOs, local governments, and communities.

MHPP activities extended beyond basic electricity provision to promote productive energy use and socio-institutional development, linking forest conservation with tangible community benefits, such as clean water, electricity, and improved livelihoods, and demonstrating that

healthy forests sustain these outcomes, thereby motivating communities to actively protect and conserve forest resources.

The projects were examined across physical, socio-economic, institutional, and business dimensions using descriptive and inductive approach to identify development patterns and sustainability factors, particularly within the water-energy-forest nexus. Each MHPP was profiled by location, implementation year, installed capacity, and number of users, and further assessed based on: (1) the level of community participation, (2) external stakeholder involvement, e.g., FOERDIA (Forestry and Environment Research and Development Agency), local government, and NGOs, and (3) funding mechanism.

Community involvement was classified into three types, as presented in Tabel 1. Meanwhile, the involvement of external parties in MHPP development as part of CBSFM is divided into five types, presented in Table 2.

Furthermore, based on funding, activities are grouped into 4 types of funding, namely:

- I. Fully self-funded by communities;
- II. Jointly funded through government budgets (central or regional) and community partnerships;

Table 1: Community involvement.

No.	Type of involvement	Code of involvement
1	Full involvement, including labor, materials, and funding	A
2	Involvement with labor and materials, without funding	B
3	Limited to planning and paid implementation roles.	C

Table 2: External parties involvement.

No.	Type of involvement	Code of involvement
1	Involved in all stages of development up to operational assistance, including financial contributions	A
2	Involved in all stages of development up to operational assistance	B
3	Involved in the planning and assistance of the construction phase	C
4	Involved only in the planning stage	D
5	Involved in financial/tool/material contribution	E

- III. Supported by a combination of government budgets, NGOs, and community partnerships;
- IV. Entirely financed by government budgets.

2.3. Analysis of Obstacles and Success Factors

Obstacles and success factors in implementing CBSFM through micro-hydro program were analyzed using qualitative and participatory approaches. Barriers were identified from recurring challenges faced by implementers, communities, and researchers across technical, social, environmental, and regulatory aspects. Success factors were derived from well-performing cases, highlighting key elements such as improved program concepts, data-driven planning, and active community participation in both planning and implementation. A thematic analysis was then applied to organize findings into major

categories of constraints and enabling factors, forming the basis for practical insights and recommendations to strengthen CBFM integrated with micro-hydro development.

3. Result and Discussion

This section summarizes the findings from field assessments of 14 MHPPs, highlighting three main aspects: system characteristics, key constraints, and lessons learned in addressing implementation challenges.

3.1. MHPP Characteristics

The data come from the MHPP program, carried out from 2009 to 2019, with different characteristics (Table 3). These characteristics include the MHPP’s capacity,

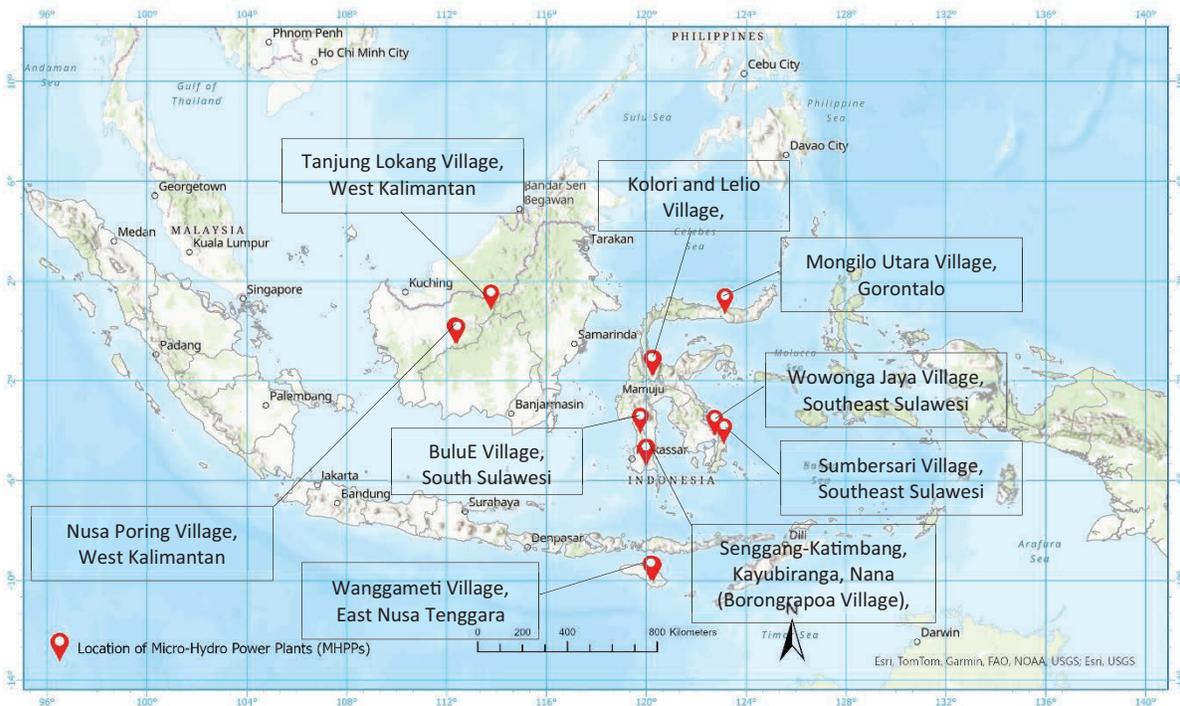


Figure 2: Map of distribution of MHPP locations.

funding sources, and the level of participation of various stakeholders, including local communities, government, and NGOs.

3.2. The Common Obstacles and Inhibiting Factors

Over the past decades, Indonesia's forest management programs have promoted micro-hydro systems to support forest conservation and renewable energy [31, 32]. Several supporting regulations have been issued to support the development of this Micro Hydro Power Plant (MHP), including Regulation of the Minister of Forestry of the Republic of Indonesia Number: P.16/Menhut-II/2014 concerning Guidelines for Area Borrowing and Use; Regulation of the Director General of Forest Protection and Nature Conservation Number: P. 07/IV-SET/2014 concerning Guidelines for Water Resource Inventory in Conservation Areas, as well as Protected Forests; Regulation of the Minister of Environment and Forestry No. 19 of 2019 concerning Water and Hydro Energy Utilization in Conservation Areas. These initiatives aim to improve energy access and livelihoods; however, micro-hydro development in forest areas encounters substantial technical, environmental, and social constraints, as also observed in studies from the Macaronesian Islands [33]. However, many government-initiated projects are not sustainable.

The study of Community-Based Microhydro Initiative (CBMI) in 14 locations showed mixed results regarding the cause of unsustainability. In several areas, the expansion of the more stable and easily managed national PLN grid, such as in Wowonga Village (North Buton) and Kolori and Lelio Villages (Tentena, Central Sulawesi), has reduced reliance on micro-hydro power plants (MHPs), resulting in neglect, underutilization, and in some cases, abandonment. In contrast, the situation in Bulukumba shows a different outcome. Despite the availability of PLN electricity, the MHP continues to operate sustainably. This resilience is attributed to strong community ownership, reflected in local financial and labor contributions during construction, as well as robust institutional management. Moreover, the productive use of MHP electricity for micro-enterprises in Bulukumba, unlike in Tentena, has strengthened its economic viability. These comparisons suggest that limited community ownership and weak institutional arrangements are key barriers to the long-term sustainability of MHP systems.

Similar challenges occurred in Nepal, where limited technical capacity and low income constrained maintenance [34]. Inadequate community skills and technical

expertise also hinder MHPP sustainability in Nigeria, Tanzania, and parts of Indonesia [35], highlighting the need for stronger capacity-building efforts by project initiators.

Performance was further hindered by design shortcomings, including inaccurate estimates of water discharge [36], as happened in Mongilo Village, in Bone Bolango Regency, and Babangeng Village in Bantaeng Regency. While government-funded MHPPs often function well, they rarely build strong public engagement in forest conservation [37]

3.2.1. Technical and Environmental Challenges

From a technical standpoint, forest areas offer strong potential for micro-hydro development due to reliable water availability and elevation differences [38-41]. Upper watershed forests typically provide year-round water and steep terrain suitable for generating electricity [42].

Technical challenges include the lack of long-term river flow and rainfall data [36], leading to an inaccurate system that overestimates flooding risk and underestimates power reduction during dry seasons. In many cases, flow estimates rely only on local oral histories and natural signs. Community enthusiasm for micro-hydro projects may lead to misinformation about water availability, risking system failure. Other barriers include difficult site access, steep terrain, and rugged river channels, which complicate construction and maintenance (Figure 4).

Post-construction challenges often arise due to the community's limited technical and institutional management capacity, leading to the shutdown of MHPPs, as similarly reported in Nepal [43], Nigeria, Tanzania, and several other MHPPs development locations in Indonesia [35, 44].

3.2.2. Social Factors Challenges

Social issues in MHPP development often arise from a top-down, project-based approach linked to funding cycles [45]. Limited community participation fosters distrust, conflict, and resistance, especially in government-funded projects managed by third parties. Such conditions can lead to project failure, reputational damage, and community boycotts [36], as also observed in Sri Lanka, where weak community involvement undermined sustainability [46]. Additional issues include unequal electricity distribution and weak post-project institutional management, particularly when externally formed, exclusive institutions limit broader community participation.

Table 3: The characteristics of MHPP in 14 different locations.

No.	Location / Year of activity *)	Unit / capacity/ household (HH)	Source of Fundings	Community Involvement	Involvement of External Parties			Existed Conditions
					FoERDIA	TIU/ RFO	NGOs	
1	Desa Kolori, Poso Regency, Central Sulawesi / 2009-2011	1 unit/ 15 KW/ 158 HH	Type II	B	B	A	–	MHPP was abandoned due to the entry of national electricity network (PLN)
2	Desa Lelio, Poso Regency, Central Sulawesi / 2009-2011	1 unit / 10 KW/ 80 HH	Type II	B	B	A	–	
3	Kampung Senggang-Katimbang, Kel. Borongrapoa, Bulukumba Regency, South Sulawesi / 2014-2019	2 unit / 12,5 KW / 28 HH	Type III	A	A	–	B	Even though the PLN electricity network is available, the low-cost MHPP is still used to support local micro-enterprises
4	Kampung Kayu Biranga, Kel. Borongrapoa, Bulukumba Regency, South Sulawesi / 2015-2019	1 unit/ 10 KW / 35 HH	Type II	A	A	–	B	
5	Kampung Nana, Kel. Borongrapoa, Bulukumba Regency, South Sulawesi / 2015-2019	1 unit/ 20 KW / 45 HH	Type I	A	A	–	B	
6	Kampung Babangeng, Kelurahan Pabumbungan, Bantaeng Regency, South Sulawesi / 2015-2019	1 unit/ 3 KW/ 15 HH	Type II	A	A	–	B	MHPP does not operate optimally during the dry season due to inaccurate design discharge estimates during planning
7	Dusun DataE, Desa BuluE, Sopeng Regency, South Sulawesi / 2017	1 unit / 50 KW/ 94 HH	Type II	A	C	A	–	Although the MHPP remains operational, its management institution has not been adequately developed and involves only a limited group of individuals.
8	Desa Wanggameti dan Desa Mahaniwa, Sumba Timur, Eat Nusa Tenggara / 2017	2 units / 40 + 6 KW/ 69+30 HH	Type II	A	C	A	–	Even though it is still operating, MHPP is not being managed properly due to the entry of the PLN electricity network.
9	Desa Wowonga Jaya, North Buton Regency / 2018	1 unit/ 25 KW/ for PUE development	Type II	A	D	A	–	
10	Desa Summersari, South Konawe Regency, South East Sulawesi / 2018	2 units/ 25 and 10 KW / 10 HH and tourist center	Type IV	C	D	A	–	Despite grid access, micro-hydro remain operating due to its cost-efficiency.

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11	Desa Nusa Poring, Melawi Regency, West Kalimantan / 2019	1 unit/ 25 KW/ 71 HH	Type IV	C	D	A	–	The MHPP is still operating today, and well managed by the community with assistance from the National Park Office.
12	Desa Mongilo Utara, Kec. Bulango Ulu, Bone Bolango Regency, Gorontalo / 2019	1 unit/ 5 KW/ 31 HH	Type IV	C	C	A	–	MHPP does not operate optimally during the dry season due to inaccurate design discharge estimates during planning
13	Desa Tanjung Lokang, Kapuas Hulu Regency, West Kalimantan / 2019	2 unit / 15+5 KW/ 125+30 HH	Type IV	C	D	A	A	The MHPP is still operating today, well managed by the community with assistance from the National Park Office
14	Desa Nusa Poring, Melawi Regency, West Kalimantan / 2019	1 Unit/ 25 KW / 70 HH	Type IV	C	C	A	–	

Noted: * The year in this column indicates the year of development as well as the year of assistance by FOERDIA.

Several photos of the MHPPs are presented in Figure 3 below.



Figure 3: The top left is MHPP in Kolori Village, Central Sulawesi; the bottom left is a MHPP in Senggang- Katimbang, Bulukumba Regency, South Sulawesi; and the right image is a MHPP in Babangeng, Bantaeng Regency, Southeast Sulawesi.



Figure 4: Extreme conditions of the MHPP location in Kolori Village, Poso Regency, Central Sulawesi.

3.3. Overcoming Problems and Challenges: Lessons Learned from Field Experience

The proposed solutions are based on social and technical data collected through interviews, focus group discussions, and field observations, as well as comparative analysis of MHPP management across study sites. This analysis identified key factors influencing success, failure, household energy supply, and rural micro-enterprises development, forming the basis for reforming incentive mechanisms in the CBSFM Program to improve sustainability, efficiency, and community ownership.

Reforming incentives is crucial to align micro-hydro development with clean energy goals, forest conservation, and local livelihoods. Strong community involvement at all stages enhances ownership, local capacity, and long-term sustainability [3], consistent with the findings on community-based renewable energy programs in the global south [35]. Micro-hydro success is closely shaped by local skills, economic conditions, and geographic context [35, 47].

In some areas, MHPP remains viable despite PLN access, as its electricity is cheaper and supports small-scale businesses. Communities often manage repairs themselves and use the power for both household and local industries. In other cases, such as in Bantaeng and Bulukumba, MHPP also promotes forest protection by

using timber from community-planted trees for household and industrial needs.

Learning from the field, we recommend five approaches to address the problems and challenges in developing micro hydropower plants: 1) Down-to-earth PES scheme, 2) Social mechanism reform, 3) Water-Energy-Food (WEF) Nexus-based activities, 4) Data-driven planning, and 3) Increasing community participation. Each approach is explained in detail as follows:

3.3.1. Down-to-earth PES Scheme

Micro-hydro development under CBSFM applies a Payment for Environmental Services (PES) scheme, recognized as an environmental economic instrument under Law No. 32/2009 [48]. In this scheme, downstream users pay the upstream community for maintaining environmental services through voluntary agreements. PES is considered suitable for participatory watershed management in Indonesia [49, 50].

Typically operating at the river basin scale, PES implementation faced challenges including limited data, high costs, policy inconsistencies, weak community capacity, and difficulties identifying legitimate service providers.

Since 2015, the Makassar for Environmental and Forestry Research and Development Center has addressed these barriers through a Participatory

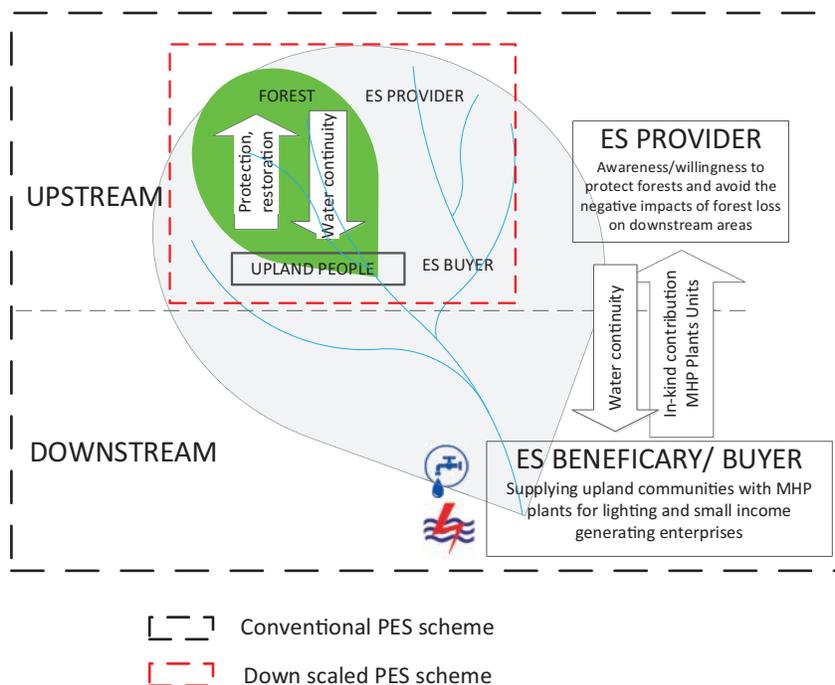


Figure 5: Operational PES concept for micro-hydro incentives scheme.

Action Research (PAR) approach, integrating micro-hydro into PES. Piloted in Bantaeng and Bulukumba (South Sulawesi), and later replicated nationally, this model links forest conservation with livelihood benefits, strengthening upstream communities’ engagement and highlighting the role of forests in maintaining water flow, energy generation, and local electricity access.

This operational PES model, CBMI, targets micro-watersheds in upper river reaches (Strahler order 1), with catchment areas up to 5,000 ha and power outputs between 3 and 50 kW. These parameters ensure manageable oversight and support independent, community-led micro-hydro operation.

In large-scale PES schemes, upstream communities act mainly as service providers. In micro-hydro-based PES, however, forest-edge communities serve as both users and co-financiers (Figure 5), sharing responsibility for maintaining the MHPP and forest functions. CBMI represent serves as a Payment for Watershed Ecosystem Services (PWES) model, applying the “3S” principles [51], Small (Implemented in micro-watersheds under 5,000 ha for easier management), Simple (clear, community-based rules and incentives), and Sinergy (promoting electrification, forest conservation, and

collaboration among communities, government, and private sectors).

To support the success of the CBMI program through PES implementation, MHPP development should focus on three key areas: unit management, environmental/area management, and locally resource-based businesses (PUE/Productive Use of Energy).

- a. MHPP unit management
Community groups independently manage and operate the micro-hydro system. They are trained to operate turbines and maintain the electricity network. The MHPP is built to be durable and easy to maintain, supporting long-term local sustainability.
- b. Environmental/ area management
To ensure water supply for the MHPP, environmental efforts include forest conservation, spring protection, and catchment area management. A key component of area management in the PWES scheme is tree planting supported by nurseries to ensure a continuous supply of seedlings (Figure 6). The development of community nurseries, combined with the community’s willingness to plant trees and the reduced pressure to encroach upon and cut down forests, creates significant opportunities for forest recovery



Figure 6: Community nurseries in Borongrapoa Village, Bulukumba Regency, as part of PWES initiatives.

- c. Business management (PUE)
Electricity is used not only for lighting but also to power local economic activities, maximizing benefits through the productive use of local resources.

3.3.2. Social Mechanism Reform: Implementing Perpetual Motion Mechanism

A Perpetual Motion Machine (PMM) is a theoretical device that runs forever without additional energy input [52]. In micro hydro development, the PMM concept is used symbolically to describe a self-sustaining social system in which community continuously operates, maintains, and reinvests benefits from the project.

Initial external support, such as funding, materials, training, and equipment (e.g., turbines, pipes), act as the starting input. Local material (wood, bamboo, stone) and community labour strengthen ownership and long-term commitment. Over time, management shifts fully to the community, which uses electricity revenues for forest conservation, capacity building, and technology improvements. As shown in Figure 7, as external supports decline by year three (h+2), community ownership

increases, creating a sustainable cycle where micro-hydro not only provides energy but also supports resilient institutions, local livelihood, and forest sustainability.

3.3.3. Water-Energy-Food (WEF) Nexus-based Activities

The Water-Energy-Food (WEF) nexus concept explains the interconnections among WEF systems and emphasizes the need for integrated management [3]. As an extension of the Integrated Water Resource Management (IWRM) and Adaptive Water Management (AWM) concepts [53, 54], it address resource scarcity by managing synergy and trade-offs to support sustainable development [3]. Recognizing these linkages helps forest managers enhance ecosystem resilience to meet community needs [55], since disruption in one sector can affect others, especially vulnerable groups [56]. Micro-hydro projects based on WEF nexus principles can align energy production with water and food needs while strengthening sustainability and rural resilience. The interlinked WEF subsystem for human needs is depicted in Figure 8.

In Nana Village, Bulukumba Regency, a potential conflict arose between the Bulukumba City Water Company (PDAM) water supply and the community's

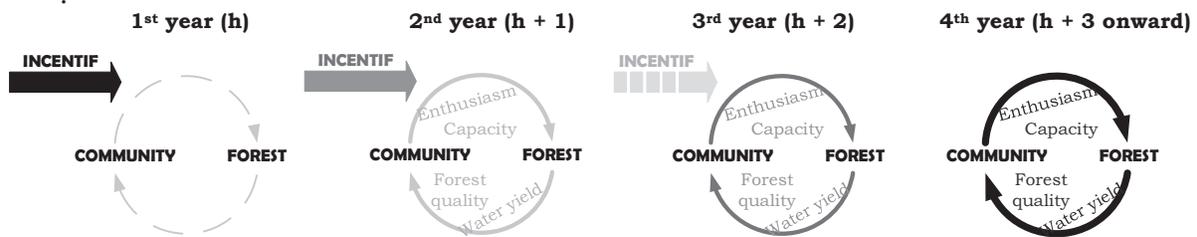


Figure 7: Perpetual motion scenarios for PWES of Micro Watershed.



Figure 8: Interlinkages of WEF in Sustainable Forest Management.

needs. To overcome this, MHPP utilizes overflow water from PDAM inlet under an agreement among residents, local government, and PDAM, ensuring adequate flow

for MHPP operations. Agricultural conflicts were avoided by placing the power plant’s inlet and outlet upstream of the irrigation intake channels, allowing water to return to the river for reuse.

Figures 9 and 10 illustrate WEF Nexus applied through the CBMI model in Borongrapoa Village, South Sulawesi. The model integrates MHPP not only for lighting but also to support PUE, supporting local economic activities such as crop processing, coffee roasting, spring bed production, and fruit syrup making.

Top image: A hybrid-powered drying hut (solar and microhydro) for drying copra in Wowonga Jaya Village, North Buton Regency.

Bottom image: A spring bed (left) and coffee industry (right) in Borongrapoa, Bulukumba Regency.

The CBMI framework’s use of the Water-Energy-Food (WEF) nexus promotes comprehensive environmental management and achieves important development objectives. It enhances resource efficiency while contributing to the Sustainable Development Goals—especially Goals

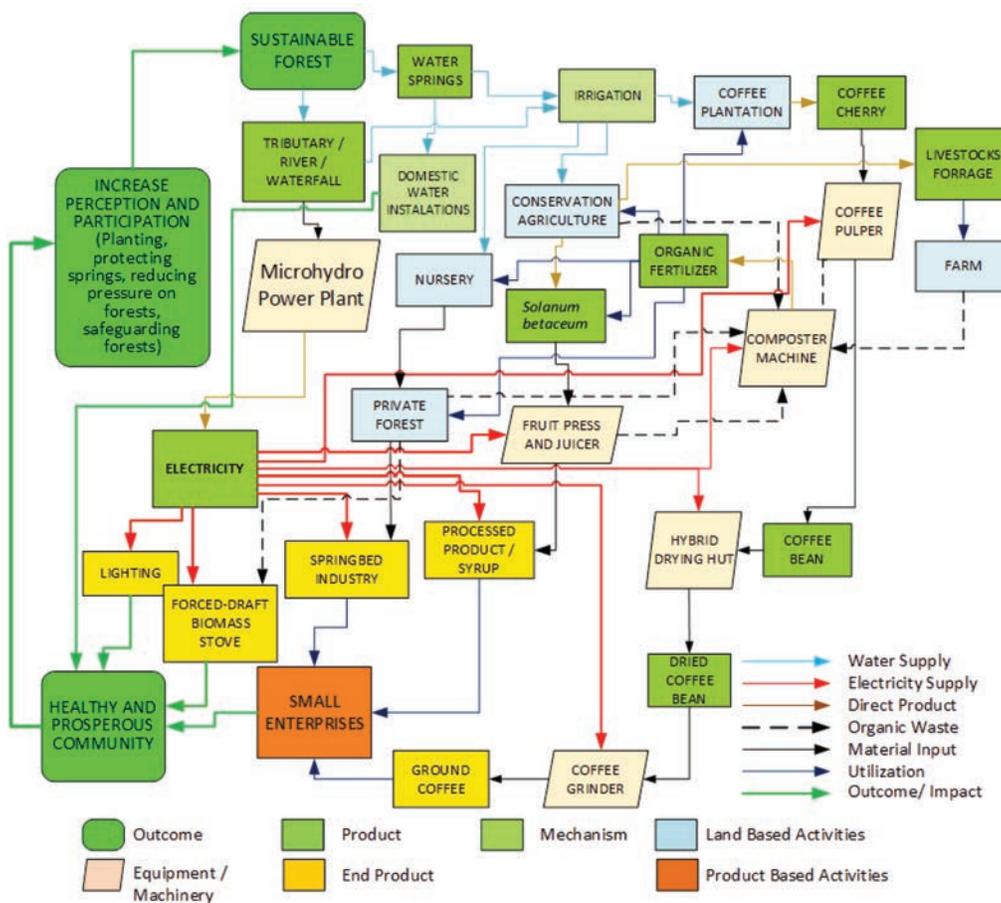


Figure 9: Implementation of the WEF Nexus within the CBMI (adapted from Nugroho, Indrawati [3]).



Figure 10: The implemented activities adopting WEF Nexus within the CBMI concept to drive local community economy.

7 (Clean Energy), 6 (Water), 2 (Zero Hunger), 9 (Education), and 13 (Climate Action). This approach improves energy access, water management, and food security, helping build sustainable and resilient communities.

3.3.4. Data-driven Planning

The success and sustainability of MHPP initiative depend on data-driven planning supported by accurate and comprehensive information [36, 57]. Effective planning requires integrating technical, socio-economic, institutional, and environmental criteria to ensure projects are feasible and reliable. This process must be backed by adequate hydrological, technical, and community data, and aligned with local conditions through collaboration among communities, government, and private sector.

The recommended data-driven planning process is outlined in Figure 11.

Technical factors, especially topography, are essential for analyzing flow, estimating power potential, and assessing landslide hazards. DEM data are used to

determine suitable sites based on head height, with an optimal head of ≥ 20 meters and at least 500 m between head points, although some studies apply 5–20 meters [58–60]. Flow analysis depends on minimum (dependable) discharge. Some studies estimate this using hydrological models like SWAT [61, 62]; SCS-CN [63], and HEC-HMS [64]. Planning also considers morphometric indicators like drainage density and Topographic Wetness Index (TWI)[18]. Power potential is calculated using head, dependable flow, system efficiency, and gravitational acceleration [42, 61].

Other key site selection challenges include institutional, socio-economic, and hazard factors. Socio-economic criteria cover operational costs, potential beneficiaries, supported economic activities, and proximity to roads, settlements, and electricity network. Common hazard risk, such as landslides, floods, and erosion must also be considered [18, 65].

Sustainable MHPPs require strong leadership, stakeholder partnership, and minimal conflict as indicator of institutional strength [66, 67]. Often overlooked, hazards and risks are critical for infrastructure sustainability

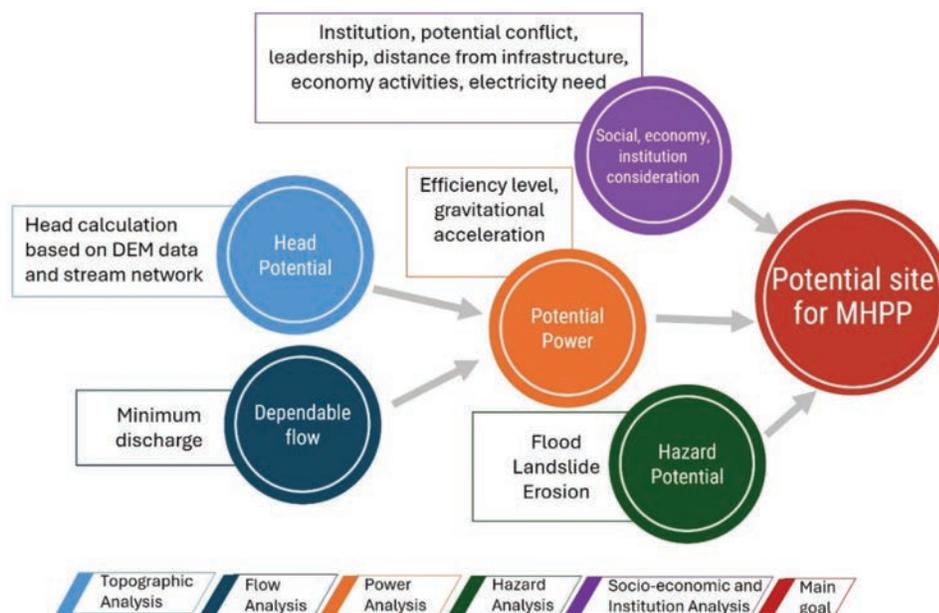


Figure 11: Potential site identification for MHPP in data-driven planning framework.

[63]. Hazards analysis should be conducted at spatial and river catchment scale where the MHPP is developed. Field surveys then guide technical design, including pipe diameter and turbine type [68]. Financial feasibility also considers equipment, construction, operations, and the added value from electricity use [69].

3.3.5. Enhancing Community Participation

Achieving genuine community involvement in government programs, particularly micro-hydro projects, remains challenges. Participation has often been limited to paid labor or passive role, with the government setting the agenda. To achieve true engagement, this approach must shift toward a more inclusive model where communities lead and the government supports (Figure 12). This change promotes greater external support, meaningful engagement, stronger local leadership, and alignment with community needs.

Field experience shows that MHPP projects often fail when communities are treated as passive recipients. Projects imposed without genuine local need or interest tend to lack ownership, resulting in underuse and abandonment, even when well funded.

Strong early community involvement, including financial contributions, donations, and participation in development and maintenance, is essential for sustainability. This aligns is consistent with Schneider, Abraham [35]’s review, who emphasize that community

engagement is key to sustainable renewable energy initiatives.

CBMI also requires adequate funding during both development and operation, as financial constraints often limit participatory approaches. MHPP feasibility depends on technical, economic, and environmental conditions. Initial investments, mainly for civil works and electro-mechanical components, typically account for 70–80% of total costs, while operation and maintenance (O&M) costs range from 1% to over 6% of total expenses [71, 72].

The costs of MHPP include planning, construction, and operation. Planning covers feasibility studies (FS) and detailed engineering designs (DED). Construction includes land preparation, labor, and materials (civil, electrical, and network). Operational cost covers technical, mechanical, and electrical maintenance.

Following the shift toward participatory approach, a cost-sharing model between communities and external actors (government or NGOs) is practical. External funding typically covers key components such as turbines, pipes, and cables, while communities contribute labor and local material (wood, bamboo, sand, and stone).

CBMI development can also be integrated into Forest and Land Rehabilitation (FLR) program, particularly within community-based forest management program under Ministry of Environment and Forestry. When

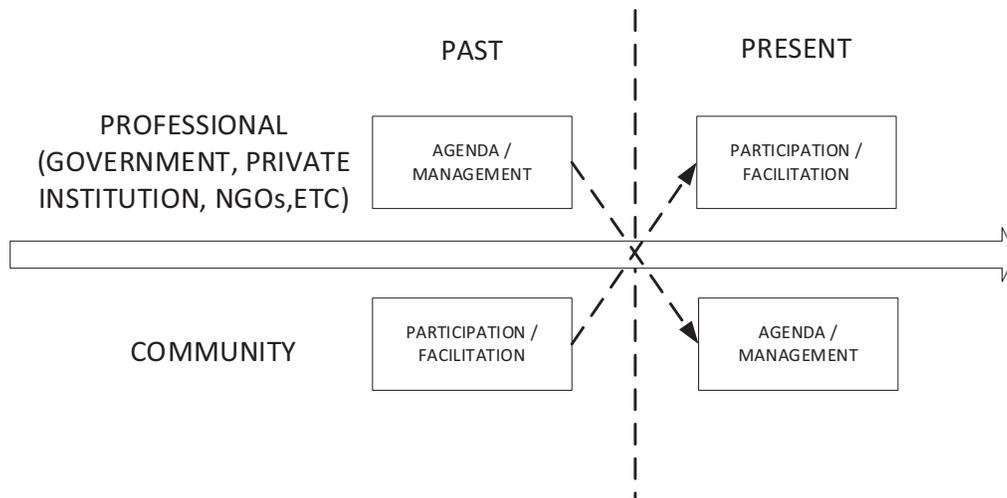


Figure 12: Paradigm shift in CBMI [70].

funded through FLR, CBMI can support reforestation efforts. Rehabilitation costs range from IDR 14–17 million/ha [73], up to IDR 43 million for 2 ha in Musi Banyuasin [74], and IDR 8.82 million/ha in West Sumatra [75]. Using this benchmark, reforesting 1,000 hectares may cost around IDR 8 billion. If 10% (IDR 800 million) is allocated to MHPP development, three units serving around 450 households each can be built. If each household plants five trees per month, about 27,000 trees could be planted per year, covering approximately 67.5 ha (400 trees/ha). This demonstrates that allocating part of FLR funds to MHPPs can support both reforestation and rural electrification.

Sustainable funding is essential to CBMI’s long-term viability. While donor or government support may help with initial construction, it is often insufficient for ongoing operations. A stronger approach relies on community-based financing through monthly user fees, covering both household electricity and PUE for small rural enterprises.

Using electricity for small businesses and homes allows for steady revenue to keep the system running. Field experience shows that self-funded projects can operate successfully, even with modest construction quality. For example, an MHPP constructed in 2015 remains operational and well managed even after the national grid arrives in 2022.

Effective operation and maintenance (O&M) is equally critical. Poor O&M can lead to costly repairs, service disruption, and safety risk. Community involvement in O&M strengthens local ownership and systems

sustainability. A typical community-based management structure includes a chairperson, secretary, treasurer, and technicians. Training in routine O&M and emergency response strengthens local capacity.

Daily monitoring is handled by trained local technicians, while larger issues are managed collectively or referred to original installer if beyond local expertise.

The long-term viability of MHPP depends on equipment condition and stable water flow. Reliable operation requires well-maintained components, such as generators, belts, penstocks, channels, and dams, supported by community contributions and collective maintenance. A steady water supply also depends on protecting upstream forests, both passively (by lowering reliance on timber) and actively (joint patrols to prevent illegal activities). Reforestation can be incorporated into community responsibilities, such as planting five trees per family each month. Government or external actors primarily provide support, such as seedlings, training, and technical assistance, and gradually reduce their involvement as community capacity grows.

A community-based approach is vital to overcoming social challenges in MHPP projects. Education builds trust, while transparent involvement of local leaders reduces resistance. Participatory decision-making and shared ownership strengthen commitment. Clear and inclusive rules for electricity use and management, developed through discussion, promote fairness and cohesion. In Borongrapoa Village, Bulukumba, a cascade MHPP system reuses water from upstream units to power downstream ones. This design reflects a social

dynamic: success in early units (Senggang-Katimbang) fosters support for later units (Kayubiranga and Nana), encouraging cooperation and competition. The model is suitable for areas with multiple settlements along one river system. CBMI success depends on strong community participation. This requires active participation at all stages, the use of simple, locally appropriate technologies, and continuous capacity building through training and knowledge transfer. for effective knowledge transfer.

4. Conclusion

Community-based MHPPs offer a practical way to integrate renewable energy into forest management. They improve rural water, energy security, and livelihoods, while creating incentives for forest conservation. By linking energy production to healthy watershed, community becomes more aware of the importance of forest ecosystems for regulating water essential to MHPP operation.

Long-term sustainability depends on strong community involvement in planning, financing, operating, and maintaining stages. Such engagement builds ownership, technical capacity, and institutional resilience. However, challenges remain, including limited hydrological data, unequal participation, and environmental risk. These require better planning, capacity building, and participatory governance.

The CBMI approach integrates PES, the “3S” principles (Small, Simple, and Synergy), a Water-Energy-Food (WEF) Nexus perspective, and blended financing from external and local sources, are strategic approach for successful MHPPs implementation. Moreover, data-driven site selection helps reduce risks and improve feasibility. From a study of 14 PLTMH, qualitatively, MHPP incentives have improved the rural economy and increased community enthusiasm for planting trees and preserving forests.

Conflicts of Interest

The authors declare no conflict of interest.

Author Contributions

All authors are main authors with a focus on the following sections:

HYSHN: Conceived the study and designed the research framework; HYSHN, WI: collected the data; HYSHN, NW, OS, WI, DA, LH: data analysis, interpretation, and visualization, drafted the manuscript, reviewed, edited, and approved the final version of the manuscript.

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