Micro Hydropower Potential Assessment for Sustainable Tourism Electrification: A Case Study of Taeno Waterfall, Ambon

Eka Rahmat Mahayani Anthonio Putera Lilipaly[1,5*], Sefnath J Wattimena[2], Sefnath J Etwan Sarwuna[3], Cendy S E Tupamahu[3], Obednego Dominggus Nara[4], Hendrik Simon Latumaerissa[1], Aprilyanto Khouw[5], Gilbert A Rumalatu[6], Azmain N Hatuwe[1,5]

[1]Mechanical Engineering Department, Ambon State Polytechnic, Maluku – Indonesia
[2]Electrical Engineering Department, Ambon State Polytechnic, Maluku – Indonesia
[3]Mechanical Engineering Department, Faculty of Engineering, Pattimura University, Maluku – Indonesia
[4]Civil Engineering Department, Ambon State Polytechnic, Maluku – Indonesia
[5]New and Renewable Energy Laboratory, Mechanical Engineering Department, Ambon State Polytechnic, Maluku – Indonesia
[6]Department of Business Administration, Ambon State Polytechnic, Maluku - Indonesia

Abstract: This study evaluates the technical and economic feasibility of micro hydropower development at Taeno Waterfall, Ambon, Indonesia, to support sustainable tourism electrification. Hydrological assessment was conducted using 10-year rainfall data (2014–2023) combined with the National Rural Electric Cooperative Association (NRECA) method to estimate streamflow in the absence of long-term discharge measurements. The results indicate an average annual rainfall of approximately 3619.92 mm and an estimated average discharge of 0.70 m³/s. Flow duration curve analysis produced dependable flows of Q50 = 0.63 m³/s, Q80 = 0.35 m³/s, and Q90 = 0.28 m³/s, confirming adequate water availability for year-round micro hydropower operation. Hydraulic analysis showed a gross head of 24 m with a net head of 22.44 m after accounting for friction and minor losses. Using a design discharge of 0.35 m³/s and an overall efficiency of 75%, the estimated electrical power output is approximately 58 kW, classified as micro hydropower. A crossflow turbine was identified as the most suitable technology due to its compatibility with medium-head and moderate-flow conditions, operational flexibility, and cost effectiveness. Estimated electricity demand for tourism facilities is approximately 30 kW peak load with annual consumption of 66 MWh, indicating that the proposed system can fully meet demand with surplus energy for future expansion. Economic analysis using the Indonesian electricity tariff of 0.086 USD/kWh yields an annual benefit of approximately 19,278 USD and a payback period of about 12 years. The findings demonstrate that Taeno Waterfall possesses strong potential for sustainable renewable energy implementation to support tourism development and local energy resilience.

Keywords: Micro hydropower, Sustainable tourism electrification, NRECA hydrological modeling, Flow duration curve, Renewable energy feasibility.
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INTRODUCTION

The increasing global demand for sustainable energy has accelerated the transition toward renewable energy systems, particularly in remote and rural regions where access to reliable electricity remains limited. Decentralized renewable energy technologies have emerged as practical solutions for electrification in such areas while minimizing environmental impacts associated with fossil fuel–based power generation. Among various renewable energy technologies, micro hydropower has gained significant attention due to its high efficiency, reliability, long operational lifespan, and relatively low operating costs

compared to other renewable sources such as solar and wind energy (Paish, 2002). Micro hydropower systems, typically defined as installations with capacities below 100 kW, are particularly suitable for remote locations with abundant water resources and favorable topographical conditions, including mountainous regions and small island environments (ESMAP, 2019).

Indonesia, as an archipelagic country with abundant hydrological resources, possesses significant potential for micro hydropower development. The country's geographical characteristics, including high rainfall intensity, steep terrain, and numerous small rivers and waterfalls, create favorable conditions for small-scale hydropower installations (Kementerian ESDM, 2020). Despite this potential, many rural communities and tourism destinations in eastern Indonesia continue to experience limited access to reliable electricity due to geographical isolation, dispersed settlements, and high infrastructure costs associated with grid expansion. This electricity gap not only constrains local economic growth but also limits the development of tourism infrastructure, which increasingly depends on stable energy supply for lighting, communication systems, water pumping, and commercial services (Bhattacharyya, 2012).

Tourism has become an important driver of regional economic development in Indonesia, contributing significantly to local income generation and employment opportunities. In recent years, the concept of sustainable tourism has gained global attention, emphasizing the integration of environmental conservation, community empowerment, and responsible resource management within tourism development strategies (UNWTO, 2018). Energy supply plays a crucial role in achieving sustainable tourism, as tourism facilities often require electricity for operational activities, visitor comfort, and safety systems. Renewable energy–based electrification of tourism destinations can reduce environmental impacts, enhance energy security, and strengthen the eco-friendly image of tourist attractions (Becken & Simmons, 2012). In particular, renewable energy installations can also serve educational purposes by demonstrating sustainable development practices to visitors while supporting local economic growth.

Maluku Province, is characterized by its small island geography, mountainous landscapes, and abundant natural water resources. Many regions within the province remain underdeveloped in terms of energy infrastructure due to logistical challenges and high costs associated with conventional power systems. At the same time, Maluku possesses considerable untapped renewable energy potential, including hydropower resources originating from forested watersheds and mountainous catchment areas. Harnessing these local energy resources through decentralized systems such as micro hydropower can significantly improve energy access while supporting regional economic activities, including tourism development (Situmorang et al., 2020).

Taeno Waterfall, located in Ambon City, Maluku Province, represents one such site with promising micro hydropower potential. The waterfall is situated within a mountainous forest environment with relatively preserved natural conditions, making it an attractive tourism destination for visitors seeking nature-based recreational experiences. The presence of significant elevation differences, continuous water flow, and proximity to tourism facilities creates favorable conditions for implementing a micro hydropower system. However, electricity availability at the site remains limited, restricting opportunities for infrastructure development such as lighting systems, food stalls, visitor facilities, and safety equipment. The integration of renewable energy systems at Taeno Waterfall could therefore support sustainable tourism development while simultaneously serving as a demonstration project for clean energy utilization in remote tourism locations.

Previous studies on micro hydropower development have primarily focused on rural electrification for residential communities, agricultural applications, or isolated village power systems. These studies have demonstrated that micro hydropower can significantly improve quality of life, economic productivity, and social development in remote areas while reducing greenhouse gas emissions compared to diesel-based generation systems (Williams & Simpson, 2009). However, relatively limited research has examined the application of micro hydropower for tourism electrification, particularly in small island contexts. Tourism sites often exhibit distinct load characteristics compared to residential communities, including variable daily demand patterns, seasonal fluctuations, and concentrated energy usage during operational hours. These characteristics require tailored system design approaches that consider both technical performance and economic sustainability within the tourism sector.

Figure 1. Taeno Waterfall

Furthermore, integrating renewable energy into tourism infrastructure aligns with global sustainable development objectives, including the United Nations Sustainable Development Goals (SDGs), particularly Goal 7 (Affordable and Clean Energy) and Goal 8 (Decent Work and Economic Growth) (United Nations, 2015). Renewable energy–powered tourism facilities can contribute to reducing greenhouse gas emissions, decreasing reliance on fossil fuel generators, and promoting environmentally responsible tourism practices. Additionally, such initiatives can enhance community participation by creating local employment opportunities in system operation, maintenance, and tourism services.

Despite the recognized potential of micro hydropower in Indonesia, site-specific feasibility assessments remain essential to ensure technical viability and economic efficiency. Hydrological variability, seasonal flow changes, terrain constraints, and infrastructure accessibility are critical factors influencing system performance and investment feasibility. Comprehensive assessments involving field measurements, hydraulic analysis, system design optimization, and techno-economic evaluation are

therefore necessary prior to implementation (ESMAP, 2019). Such studies not only support project development but also contribute to scientific knowledge regarding renewable energy applications in emerging tourism contexts.

This study aims to assess the micro hydropower potential at Taeno Waterfall in Ambon City as a sustainable energy solution for tourism electrification. The research focuses on evaluating hydrological characteristics, estimating available hydraulic power, designing an appropriate micro hydropower system configuration, and analyzing the techno-economic feasibility of the proposed installation. In addition, the study examines the potential contribution of renewable energy integration to sustainable tourism development in the region. By combining technical analysis with economic considerations, this research seeks to provide a comprehensive framework for implementing micro hydropower systems in similar tourism environments, particularly in small island regions with limited energy infrastructure.

The findings of this study are expected to contribute to the development of renewable energy–based tourism models in Indonesia, support local government planning initiatives, and provide reference data for future micro hydropower projects in Maluku Province. Moreover, the research may serve as a foundation for further studies on hybrid renewable energy systems, environmental impact assessments, and community-based energy management approaches in tourism destinations. Ultimately, the integration of micro hydropower at Taeno Waterfall has the potential to demonstrate how renewable energy technologies can support sustainable tourism while promoting energy independence and environmental conservation in remote island regions.

RESEARCH METHOD
Micro Hydropower for Decentralized Energy Systems

Access to reliable and affordable electricity remains a major challenge in many remote and rural regions worldwide, particularly in developing countries characterized by dispersed populations and limited infrastructure. Decentralized renewable energy systems have emerged as viable alternatives to conventional grid extension, offering localized power generation that can be tailored to community needs. Among these technologies, micro hydropower has gained considerable attention due to its technical maturity, high conversion efficiency, and long operational lifespan compared with other renewable energy technologies such as solar photovoltaic and wind power (Paish, 2002).

Micro hydropower systems are typically classified as installations with capacities below 100 kW, although definitions may vary across countries and institutions. These systems convert the potential energy of flowing or falling water into electrical energy through turbines and generators, enabling continuous electricity generation when sufficient water resources are available. One of the main advantages of micro hydropower is its relatively stable output compared to intermittent renewable sources, making it particularly suitable for applications requiring reliable power supply, including rural communities, agricultural processing, and tourism facilities (Williams & Simpson, 2009).

In developing regions, micro hydropower has demonstrated significant socio-economic benefits, including improved household welfare, increased productivity of local enterprises, and enhanced access to education and healthcare services. Studies have shown that electrification through decentralized renewable energy systems contributes positively to poverty reduction and sustainable development outcomes (Bhattacharyya, 2012). Furthermore, micro hydropower systems often exhibit lower life-cycle costs compared to diesel generators due to minimal fuel requirements and reduced maintenance complexity, particularly in locations with abundant water resources.

Indonesia possesses substantial micro hydropower potential due to its tropical climate, mountainous terrain, and extensive river networks. However, much of this potential remains untapped, especially in eastern regions such as Maluku and Papua where infrastructure development is constrained by geographical and logistical challenges. Harnessing local hydropower resources through decentralized systems offers a promising pathway to improve energy access while supporting regional economic development (Situmorang et al., 2020).

Renewable Energy Integration in Sustainable Tourism

Tourism is recognized as one of the fastest-growing economic sectors globally, contributing significantly to employment, income generation, and regional development. However, tourism activities also consume substantial amounts of energy, particularly for accommodation, transportation, lighting, water supply, and recreational services. Conventional energy sources used in tourism infrastructure, such as diesel generators, contribute to greenhouse gas emissions, environmental degradation, and operational costs that may undermine long-term sustainability (Becken & Simmons, 2012).

The concept of sustainable tourism emphasizes the need to balance economic growth with environmental protection and social equity. Renewable energy adoption plays a critical role in achieving sustainable tourism objectives by reducing carbon emissions, improving energy security, and enhancing environmental performance of tourism destinations. Renewable energy systems also contribute to eco-friendly branding, which increasingly influences tourist preferences and destination competitiveness (UNWTO, 2018).

Nature-based tourism sites located near rivers, waterfalls, or mountainous regions present unique opportunities for integrating renewable energy technologies such as micro hydropower. Unlike conventional energy infrastructure, micro hydropower installations can operate with minimal visual impact when properly designed, preserving the aesthetic value of natural landscapes. Additionally, renewable energy systems can serve educational purposes by demonstrating sustainable technologies to visitors, thereby increasing environmental awareness and community engagement.

Despite these advantages, research focusing on renewable energy implementation specifically for tourism electrification remains relatively limited. Most existing studies concentrate on rural residential electrification or hybrid renewable energy systems for isolated communities. Tourism facilities often exhibit unique load characteristics, including seasonal fluctuations and concentrated demand during operating hours, requiring tailored energy system designs.

Hydropower Resource Assessment

The feasibility of micro hydropower systems depends primarily on two key parameters: water discharge (flow rate) and hydraulic head. The theoretical power available from a hydropower site can be calculated using the equation:

$$P = \rho g Q H \eta \tag{1}$$

where P is power output, ρ is water density, g is gravitational acceleration, Q is discharge, H is effective head, and η represents system efficiency (ESMAP, 2019). Accurate estimation of these parameters is essential for determining technical feasibility and economic viability. Hydrological conditions in tropical regions are often characterized by seasonal variability influenced by rainfall patterns, watershed characteristics, and land use changes. Consequently, long-term hydrological data analysis is necessary to ensure reliable system

design and prevent overestimation of energy potential. In many remote regions, however, hydrological measurement data are limited or unavailable, requiring the use of estimation methods based on rainfall and watershed characteristics (World Bank, 2016).

Dependable Flow and Flow Duration Curve Analysis
Dependable flow is a critical parameter in hydropower design, representing the flow rate that can be expected to be equaled or exceeded for a specified percentage of time. It is commonly expressed as Q80, Q90, or Q95, indicating availability during 80%, 90%, or 95% of the time, respectively (Shrestha et al., 2010). Dependable flow analysis ensures that hydropower systems can operate consistently even during low-flow conditions, which is particularly important for standalone micro hydropower installations serving continuous loads.

The flow duration curve (FDC) is widely used to evaluate hydrological variability and determine appropriate design discharge. The FDC plots flow magnitude against exceedance probability, providing insights into flow reliability over time. This tool enables designers to balance energy production and system reliability by selecting an appropriate design discharge based on project objectives. For micro hydropower systems, design discharge is often selected between Q40 and Q70 to optimize energy output while maintaining reliability during seasonal variations (ESMAP, 2019).

In cases where measured discharge data are unavailable, synthetic flow duration curves may be developed using rainfall-runoff models or empirical estimation methods. These approaches are commonly used in feasibility studies for small hydropower projects in developing countries.

NRECA Method for Hydrological Estimation
The National Rural Electric Cooperative Association (NRECA) method is widely used for estimating river discharge in ungauged watersheds where hydrological measurement data are unavailable. Originally developed for rural electrification planning, the NRECA method uses rainfall data, watershed area, evapotranspiration estimates, and runoff coefficients to calculate monthly streamflow (NRECA, 1989).

The method is based on water balance principles, considering precipitation input, soil moisture storage, evapotranspiration losses, groundwater recharge, and surface runoff. Monthly runoff is estimated and converted into discharge using watershed area parameters. Although the method provides approximate results, it is considered sufficiently accurate for preliminary feasibility studies when direct measurements are limited (Shrestha et al., 2010).

The NRECA method has been applied in numerous micro hydropower feasibility studies in tropical regions due to its simplicity and practicality. However, the accuracy of the method depends heavily on rainfall data quality and watershed parameter assumptions. Calibration using field measurements is recommended whenever possible to improve reliability.

Turbine Technology for Micro Hydropower
Turbine selection plays a critical role in micro hydropower system performance. Turbine type is primarily determined by available head and flow conditions. Impulse turbines such as Pelton and Turgo are suitable for high-head, low-flow conditions, while reaction turbines such as Francis and Kaplan are appropriate for medium- to low-head applications with higher flow rates (ESMAP, 2019).

For small-scale installations in remote areas, crossflow turbines are often preferred due to their simple construction, ease of maintenance, and tolerance to flow variations and debris (Williams & Simpson, 2009). Crossflow turbines also exhibit relatively high efficiency across a wide range of operating conditions, making them suitable for micro hydropower applications with fluctuating flow rates.

Recent technological developments have improved turbine efficiency and reduced manufacturing costs, increasing the feasibility of micro hydropower projects in developing regions. Locally manufactured turbines can further reduce costs and promote community participation in system maintenance.

System Configuration and Hybrid Renewable Energy Integration

Standalone micro hydropower systems may experience reduced output during dry seasons, particularly in regions with significant seasonal hydrological variability. Hybrid renewable energy systems combining micro hydropower with solar photovoltaic and battery storage have been proposed to improve reliability and energy security (ESMAP, 2019).

Hybrid systems can optimize energy production by utilizing complementary resource availability. For example, solar radiation is typically higher during dry seasons when water availability may be reduced. Integrating multiple renewable energy sources can therefore enhance system resilience while reducing dependence on fossil fuel backup generators.

Energy management systems play an important role in hybrid configurations by balancing energy generation, storage, and load demand. Advances in power electronics and control technologies have significantly improved the performance and feasibility of hybrid renewable energy systems in remote locations.

Techno-Economic Evaluation of Micro Hydropower Projects

Techno-economic analysis is essential for evaluating the feasibility of micro hydropower installations. Economic indicators commonly used include Net Present Value (NPV), Internal Rate of Return (IRR), Payback Period (PP), and Levelized Cost of Energy (LCOE) (Short et al., 1995). These parameters provide insights into project profitability, investment risk, and long-term sustainability.

Micro hydropower systems typically involve high initial capital costs but low operational costs compared to diesel-based generation systems. When fuel transportation costs and maintenance requirements are considered, renewable energy systems often become economically competitive in remote locations (Bhattacharyya, 2012).

Economic feasibility is influenced by factors such as site accessibility, equipment costs, civil construction requirements, and load demand characteristics. Tourism electrification projects may benefit from additional revenue streams generated through increased visitor numbers and service development.

Environmental and Sustainability Considerations

Micro hydropower systems are generally considered environmentally friendly compared to large hydropower projects because they involve minimal water storage and limited ecosystem disruption. Run-of-river systems, commonly used in micro hydropower applications, maintain natural river flow patterns while extracting energy from available head differences (Paish, 2002).

Environmental benefits include reduced greenhouse gas emissions, improved air quality, and decreased reliance on fossil fuels. Renewable energy adoption in tourism facilities also contributes to environmental education and awareness among visitors.

However, environmental assessments are still necessary to evaluate potential impacts on aquatic ecosystems, sediment transport, and landscape aesthetics.

Research Gap and Study Contribution

Although numerous studies have investigated micro hydropower for rural electrification, limited research has focused on its application for tourism electrification in small island environments such as Maluku. Tourism facilities exhibit unique load characteristics and sustainability objectives that differ from residential applications. Furthermore, site-specific studies integrating hydrological assessment, dependable flow analysis, system design, and techno-economic evaluation within tourism contexts remain scarce.

This study addresses these gaps by assessing micro hydropower potential at Taeno Waterfall in Ambon, integrating hydrological analysis, system design, and techno-economic evaluation to support sustainable tourism electrification. The research contributes to the development of renewable energy–based tourism models in small island regions while providing practical insights for policymakers and project developers.

Research Approach

This study employed a quantitative engineering approach to evaluate the micro hydropower potential at Taeno Waterfall, Ambon, Indonesia, for sustainable tourism electrification. The methodology consisted of field measurements, hydrological modeling, technical system design, and techno-economic analysis. The research framework is shown conceptually as follows:
1. Site survey and field data collection
2. Hydrological analysis using field measurement and NRECA method
3. Dependable flow and flow duration curve analysis
4. Hydraulic head determination
5. Micro hydropower system design
6. Energy production estimation
7. Techno-economic feasibility evaluation

Site Description and Survey

The study location is Taeno Waterfall, located in Ambon City, Maluku Province, Indonesia. A preliminary site survey was conducted to identify potential intake points, penstock routes, and turbine installation locations. Geographic coordinates were recorded using a Global Positioning System (GPS) device.
Survey parameters included:
- Elevation profile
- River width and depth
- Flow velocity
- Distance from intake to powerhouse
- Accessibility conditions
- Environmental constraints

Field Data Collection
Flow Measurement Using Flow Meter

Water discharge was measured directly using a portable current flow meter to obtain accurate hydrological data. Measurements were conducted at selected cross-sections along the stream near the proposed intake location.

The discharge was calculated using the velocity–area method:

$$Q = A \times V \tag{2}$$

Where:
- Q= discharge (m³/s)
- A= cross-sectional area (m²)
- V= average flow velocity (m/s)

The cross-sectional area was determined by dividing the river width into multiple segments and measuring water depth at each segment. The area was calculated as:

$$A = \sum(d_i \times w_i) \tag{3}$$

Where:
- d_i= depth at segment i(m)
- w_i= width of segment i(m)

Flow velocity was measured at 0.6 of water depth from the surface for shallow streams or at 0.2 and 0.8 depth positions for deeper sections, following standard hydrological measurement procedures (World Bank, 2016).

Multiple measurements were conducted to account for temporal variability and improve accuracy. The average discharge value was used as the representative flow for analysis.

Head Measurement

Hydraulic head represents the vertical elevation difference between the intake point and the turbine location. Gross head was measured using a combination of GPS elevation data and a laser distance meter. Net head was determined by subtracting head losses caused by friction and turbulence within the penstock.

Head loss was calculated using the Darcy–Weisbach equation:

$$h_f = f \frac{L}{D} \frac{V^2}{2g}$$

Where:
- h_f= head loss (m)
- f= friction factor
- L= pipe length (m)
- D= pipe diameter (m)
- V= flow velocity (m/s)
- g= gravitational acceleration (9.81 m/s²)

The effective head was calculated as:

$$H_{net} = H_{gross} - h_f \tag{4}$$

Tourism Load Assessment

Electricity demand was estimated based on field observation and interviews with local stakeholders. The load components included:
- Lighting systems
- Food stalls and kiosks
- Charging stations
- Water pumps
- Public facilities (toilets, ticket office)

- Future expansion loads
  Daily energy consumption was calculated using:

$$E = \sum(P_i \times t_i) \tag{5}$$

Where:
- E = daily energy demand (kWh)
- P_i = power rating of equipment (kW)
- t_i = operating time (hours/day)

Hydrological Analysis Using NRECA Method

When long-term discharge data are unavailable, hydrological estimation was performed using the National Rural Electric Cooperative Association (NRECA) method. This method estimates monthly streamflow based on rainfall data and watershed characteristics.

Water Balance Equation

The basic water balance equation is:

$$P = ET + Q + \Delta S \tag{6}$$

Where:
- P = precipitation (mm)
- ET = evapotranspiration (mm)
- Q = runoff (mm)
- ΔS = change in soil moisture storage (mm)

Runoff Estimation

Monthly runoff was estimated using:

$$RO = C_r \times (P - ET) \tag{7}$$

Where:
- RO = runoff (mm)
- C_r = runoff coefficient
- P = precipitation (mm)
- ET = evapotranspiration (mm)

The runoff coefficient depends on watershed characteristics such as soil type, slope, vegetation, and land use.

Conversion to Discharge

Runoff depth was converted into discharge using watershed area:

$$Q = \frac{RO \times A}{t}$$

Where:
- Q = discharge (m³/s)
- RO = runoff (m)
- A = watershed area (m²)
- t = time (seconds)

Monthly discharge values were then used to estimate annual flow patterns.

Dependable Flow and Flow Duration Curve
    Dependable flow was determined by constructing a flow duration curve (FDC) based on monthly discharge data. The steps included:
1. Sorting discharge data from highest to lowest
2. Assigning probability of exceedance using:

$$P = \frac{m}{n+1} \times 100\% \tag{8}$$

Where:
- P= probability of exceedance (%)
- m= rank order
- n= total number of observations

Dependable flows such as Q80 or Q90 were obtained from the FDC for system design.

Hydropower Potential Calculation
    The potential power output was calculated using equation (1). Efficiency values were assumed based on turbine type and generator characteristics.

Turbine Selection
    Turbine type selection was based on head and flow conditions following standard turbine selection charts. Crossflow or Pelton turbines were considered due to their suitability for medium-to-high head and moderate flow conditions commonly found in waterfall environments (ESMAP, 2019).

Energy Production Estimation
Annual energy production was calculated using:

$$E_{annual} = P \times CF \times 8760 \tag{9}$$

Where:
- CF= capacity factor
- 8760 = hours per year

Capacity factor was estimated based on seasonal flow availability.

Techno-Economic Analysis
Economic feasibility was evaluated using standard indicators:
Net Present Value (NPV)

$$NPV = \sum \frac{B_t - C_t}{(1+r)^t} \tag{10}$$

Internal Rate of Return (IRR)
IRR was calculated as the discount rate where NPV equals zero.
Levelized Cost of Energy (LCOE)

$$LCOE = \frac{\sum(I_t + O_t + F_t)}{\sum E_t} \tag{11}$$

Where:
- I_t= investment cost
- O_t= operation cost
- F_t= fuel cost (if any)
- E_t= energy produced

These indicators were used to assess economic feasibility compared with alternative energy sources such as diesel generators.

Environmental Considerations

Environmental assessment focused on potential impacts on river flow, aquatic ecosystems, and landscape aesthetics. A run-of-river system configuration was considered to minimize environmental disturbance.

RESULT AND DISCUSSION

Site Characteristics and Field Measurement Results

This study was conducted at Taeno Waterfall, located in Ambon City, Maluku Province, Indonesia. Field surveys were performed to obtain primary data related to hydrological conditions, elevation differences, and potential installation locations for micro hydropower components. The selected intake location was determined based on water flow concentration, accessibility, and elevation suitability relative to the proposed powerhouse location.

The river cross-section was divided into six segments to determine the wetted area using the depth–width method. Depth measurements were taken at the boundaries of each segment, and the average depth was calculated to determine the cross-sectional area.

Table 1. River Cross-Sectional Area

| Section	Depth 1 (m)	Depth 2 (m)	Average Depth (m)	Width (m)	Area (m²)
1	0.00	0.57	0.285	1.23	0.35
2	0.57	0.50	0.535	1.23	0.66
3	0.50	0.84	0.670	1.23	0.83
4	0.84	1.02	0.930	1.23	1.15
5	1.02	0.73	0.875	1.23	1.08
6	0.73	0.00	0.365	1.23	0.45
Total River Cross-Sectional Area					**4.51**

Flow velocity measurements obtained using a current flow meter at multiple points resulted in an average velocity of 0.42 m/s. Based on the velocity–area method, the measured discharge was calculated as 1.88 m³/s during the survey period.

Seasonal variation is an important consideration in micro hydropower planning. Therefore, repeated measurements or hydrological modeling were used to estimate minimum and maximum discharge conditions. The field measurement results suggest that the stream exhibits relatively stable flow characteristics due to its upstream forest catchment area, which provides natural water retention and gradual runoff release.

Figure 1. Area and Flow Field Measurement

Figure 2. Map of Taeno Waterfall
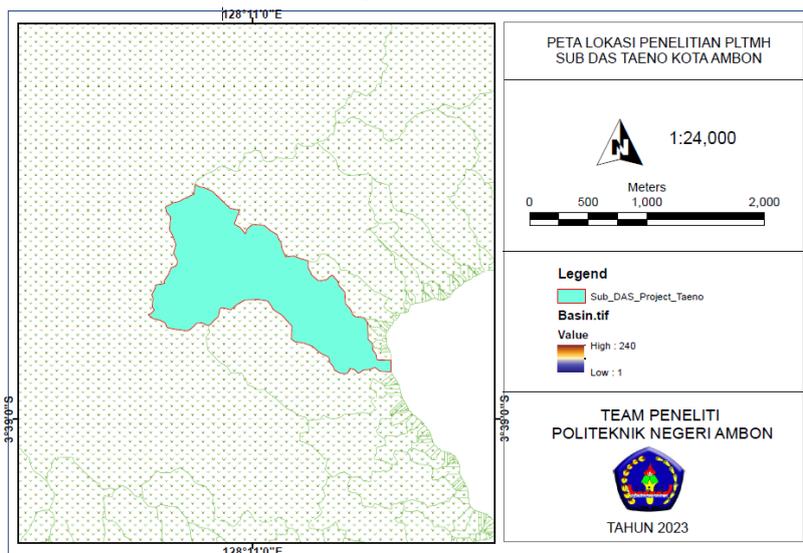
Hydrological Analysis Using NRECA Method

In addition to field measurements, hydrological analysis was conducted using the National Rural Electric Cooperative Association (NRECA) method to estimate monthly discharge variations throughout the year. Rainfall data obtained from the nearest meteorological station were used as primary input parameters.

Table 2. 2014-2023 Monthly Average Rainfall Data

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2014	302.3	178.2	60.3	123.4	329.1	397.4	220.5	482.9	118.1	126.7	31.2	133.3
2015	160.3	195.6	120.0	116.6	310.6	182.4	659.2	167.6	70.1	3.0	67.1	13.6
2016	117.7	70.1	33.5	131.8	372.0	231.7	206.1	925.5	321.8	363.1	185.2	37.0

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2017	118.8	168.2	266.8	140.0	221.5	646.9	1541.8	1050.0	443.2	508.8	182.4	143.7
2018	212.2	226.7	97.9	198.9	291.2	732.5	843.0	656.5	299.0	410.4	29.7	26.2
2019	145.3	198.2	86.2	209.2	276.3	249.8	592.2	257.9	93.6	86.0	190.9	31.5
2020	14.2	32.3	96.1	184.4	107.8	677.2	839.7	938.7	308.8	588.5	444.4	136.7
2021	139.4	114.5	89.5	105.0	111.6	807.7	522.5	1336.7	902.8	675.3	237.7	181.6
2022	265.5	82.4	91.9	128.9	139.8	143.8	336.5	1155.5	822.2	482.5	52.5	138.6
2023	266.4	157.7	182.7	189.9	296.1	413.1	737.2	514.3	231.5	195.4	93.5	49.8

Table 3. Average Monthly Rainfall Data

Month	Average Rainfall (mm)
Jan	174.21
Feb	142.39
Mar	112.49
Apr	152.81
May	245.60
Jun	448.25
Jul	649.87
Aug	748.56
Sep	361.11
Oct	344.97
Nov	151.46
Dec	89.20

The rainfall characteristics of the Taeno watershed were analyzed using the 10-year monthly rainfall dataset presented in Table 2 and the calculated average monthly rainfall values summarized in Table 3. The dataset indicates significant temporal variability in precipitation both seasonally and annually, reflecting the tropical climatic conditions typical of the Maluku region.

The average annual rainfall calculated from the dataset is approximately **3619.92 mm/year**, which indicates a high precipitation regime compared with many regions in Indonesia. Such high rainfall levels are advantageous for hydropower development because precipitation directly influences watershed runoff and streamflow availability (Shaw, 1994). The substantial rainfall also suggests strong groundwater recharge potential, which contributes to maintaining baseflow during dry periods.

Seasonal rainfall patterns derived from Table 3 show that precipitation is not uniformly distributed throughout the year. The highest average rainfall occurs between **June and August**, with peak values recorded in August (748.56 mm) and July (649.87 mm). This period corresponds to the wet season in the region and is expected to produce the highest river discharge and hydropower generation potential. Conversely, lower rainfall values are observed during **December to March**, with the minimum occurring in

December (89.20 mm). These months represent potential low-flow periods that may reduce hydropower output if system design does not consider dependable flow conditions.

Interannual variability is also evident in Table 2, where extreme rainfall events occur in certain years. For example, July 2017 recorded rainfall exceeding 1500 mm, which is significantly higher than the average monthly rainfall. Such extreme precipitation events may lead to temporary increases in river discharge but also introduce potential risks such as flooding, sediment transport, and infrastructure stress. Therefore, long-term average rainfall values are more appropriate for hydrological modeling and system design than individual extreme events (World Bank, 2016).

The rainfall distribution pattern indicates a monsoonal influence with a pronounced wet season during mid-year months. This seasonal pattern directly affects runoff generation and river flow behavior, making it essential to incorporate rainfall variability into hydrological modeling using approaches such as the NRECA method. The use of average monthly rainfall data from Table 3 provides a representative long-term precipitation input for runoff estimation while minimizing the influence of anomalous years.

From a hydropower perspective, the rainfall characteristics observed in Tables 2 and 3 suggest favorable conditions for micro hydropower development. The high annual rainfall combined with significant monthly precipitation during wet seasons supports sustained runoff generation, while groundwater storage mechanisms help maintain streamflow during lower rainfall periods. These conditions are consistent with hydrologically suitable micro hydropower sites identified in tropical mountainous regions (Paish, 2002).

However, seasonal variability remains an important consideration for system reliability. Lower rainfall months may reduce available discharge, which highlights the importance of selecting a dependable design flow such as Q80 or Q90 to ensure continuous operation. Additionally, hybrid renewable energy integration, such as combining micro hydropower with solar photovoltaic systems, could further improve energy reliability during extended dry periods.

Overall, the rainfall analysis confirms that the Taeno watershed possesses adequate hydrological potential to support micro hydropower generation, with precipitation levels sufficient to sustain streamflow throughout most of the year. The rainfall data provided a reliable basis for subsequent runoff estimation and dependable flow analysis using the NRECA model.

Table 4. NRECA Input Parameters

Parameter	Value	Unit
Watershed Area	7.71	km²
Runoff Coefficient (C)	0.25	—
Crop Coefficient (Kc)	1.00	—
Subsurface Flow Coefficient (PSUB)	0.30	—
Groundwater Factor (GWF)	0.40	—
Soil Moisture Storage (SMSTOR)	200	mm
Baseflow Storage (BSG)	10	mm
Nominal Parameter	1005	—
Annual Rainfall	3619.92	mm

The monthly rainfall variation for the period 2014–2023 is presented in Figure 3. The dataset shows significant temporal variability with several high-intensity rainfall events exceeding 1000 mm/month, particularly during mid-year periods. Such rainfall patterns are typical of tropical climates and strongly influence watershed runoff behavior and river discharge availability.

Figure 3. Monthly rainfall distribution for the Taeno watershed from 2014 to 2023.
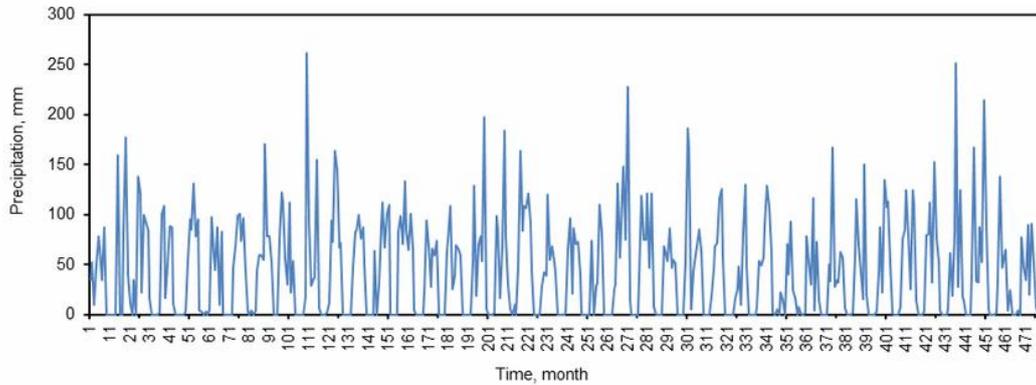
The rainfall pattern indicates peak precipitation occurring between June and August, which corresponds to increased runoff and higher river discharge during these months. Conversely, lower rainfall periods occur toward the end of the year, potentially reducing streamflow availability. Understanding this seasonal variability is essential for micro hydropower planning because discharge fluctuations directly affect energy production potential (Shaw, 1994).

Runoff Estimation Using NRECA Method
The NRECA water balance equation is expressed as:
$$P = ET + RO + \Delta S$$

Where:
- P= precipitation (mm)
- ET= evapotranspiration (mm)
- RO= runoff (mm)
- ΔS= change in storage (mm)

(NRECA, 1989)
Runoff depth was calculated using:
$$RO = C(P - ET)$$

(Shrestha et al., 2010)
Based on watershed characteristics and a runoff coefficient of 0.25, monthly runoff values were estimated.

4.X.4 Conversion to River Discharge
Runoff was converted into discharge using watershed area:
$$Q = \frac{RO \times A}{t}$$

Where:
- Q= discharge (m³/s)

- RO= runoff (m)
- A= watershed area (m²)
- t= time (seconds)

(World Bank, 2016)

Watershed area:

$$A = 7.71 \times 10^6 \text{ m}^2$$

The estimated average discharge was:

$$Q_{avg} \approx 0.70 \text{ m}^3/s$$

Estimated Monthly Discharge

Table 5. Estimated Monthly Discharge Using NRECA Model

Month	Discharge (m³/s)
Jan	0.41
Feb	0.34
Mar	0.27
Apr	0.37
May	0.60
Jun	1.10
Jul	1.60
Aug	1.84
Sep	0.89
Oct	0.85
Nov	0.37
Dec	0.22

The estimated monthly discharge of the Taeno stream derived from the NRECA hydrological model is presented in Table X. The discharge values range from **0.22 m³/s** to **1.84 m³/s**, indicating substantial seasonal variability influenced by rainfall distribution and watershed characteristics.

The highest discharge occurs during **August (1.84 m³/s)** and **July (1.60 m³/s)**, which correspond to the peak rainfall period identified in the rainfall analysis. This relationship confirms the strong dependency between precipitation intensity and runoff generation within the watershed. Similarly, elevated discharge values during **June (1.10 m³/s)** and **September (0.89 m³/s)** reflect transitional wet-season conditions, where soil moisture storage and groundwater contributions sustain streamflow even as rainfall begins to decline.

Conversely, the lowest discharge occurs during **December (0.22 m³/s)** and **March (0.27 m³/s)**, representing potential dry-season conditions. During these periods, reduced precipitation combined with increased evapotranspiration may limit runoff generation, resulting in decreased streamflow availability. However, the presence of measurable discharge throughout all months suggests that the watershed maintains baseflow contributions, likely supported by groundwater storage and forested catchment characteristics. This continuous flow availability is advantageous for micro hydropower

applications because it allows year-round energy production with minimal interruption (Paish, 2002).

The average annual discharge calculated from the monthly data is approximately **0.70 m³/s**, indicating moderate flow conditions suitable for small-scale hydropower generation. Seasonal variability remains significant, with peak flows nearly eight times greater than minimum flows. Such variability highlights the importance of selecting an appropriate design discharge based on dependable flow analysis rather than average flow alone. Hydropower systems designed using average discharge may experience reduced performance during low-flow periods; therefore, dependable discharge values such as Q80 or Q90 are typically recommended for run-of-river micro hydropower systems (ESMAP, 2019).

Overall, the discharge analysis demonstrates that the Taeno watershed possesses adequate hydrological conditions to support micro hydropower development. The combination of sustained baseflow, moderate average discharge, and high peak flow during wet seasons provides a strong foundation for reliable energy generation, particularly when system design incorporates dependable flow considerations.

Dependable Flow Analysis

Dependable flow was determined using the Flow Duration Curve (FDC) method by ranking discharge values from highest to lowest and calculating exceedance probability using:

$$P = \frac{m}{n+1} \times 100\%$$

(Vogel & Fennessey, 1994)

From the analysis, the dependable flows were obtained as:

- **Q50 = 0.63 m³/s**
- **Q80 = 0.35 m³/s**
- **Q90 = 0.28 m³/s**

The Q80 value was selected as the design discharge because it provides a balance between energy production and reliability for micro hydropower systems (ESMAP, 2019).

Flow Duration Curve (FDC)

The Flow Duration Curve developed from NRECA discharge estimation is presented in Figure 4. The FDC represents the percentage of time that a given discharge is equaled or exceeded and is widely used for hydropower resource assessment and design flow selection.

Table 6. Flow Duration Curve Data

Rank	Discharge (m³/s)	Exceedance Probability (%)
1	1.84	7.69
2	1.60	15.38
3	1.10	23.08
4	0.89	30.77
5	0.85	38.46
6	0.60	46.15
7	0.41	53.85

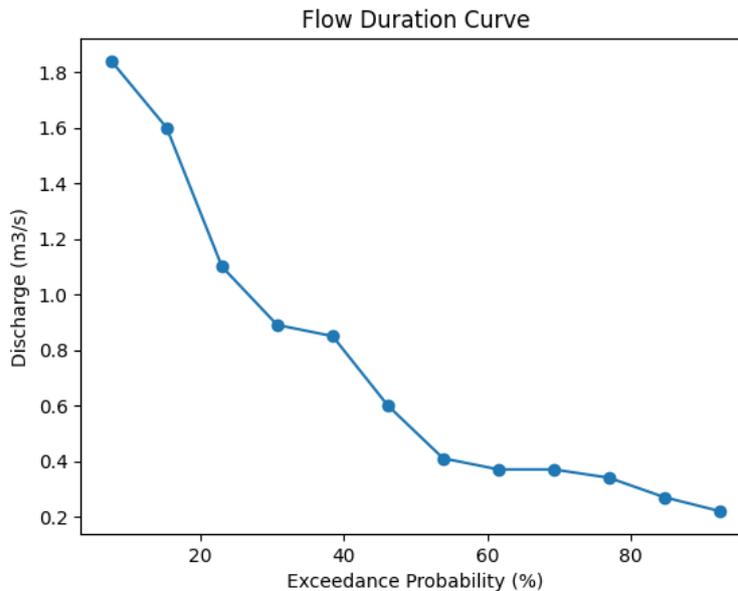| Rank	Discharge (m³/s)	Exceedance Probability (%)
8	0.37	61.54
9	0.37	69.23
10	0.34	76.92
11	0.27	84.62
12	0.22	92.31

Figure 4. Flow Duration Curve of Taeno stream based on NRECA discharge estimation.

The curve shows that discharge exceeds 0.35 m³/s for approximately 80% of the time, indicating relatively stable water availability throughout the year. Higher flows occur during peak rainfall months, while lower flows are observed during transitional seasons. This characteristic is favorable for run-of-river micro hydropower systems because dependable flow conditions can sustain continuous energy production (Vogel & Fennessey, 1994).

The NRECA results showed reasonable agreement with field measurements, indicating that the hydrological model provides a reliable representation of seasonal water availability at the study site.

Hydraulic Head and Penstock Analysis
Hydraulic Head Determination

The available hydraulic head at the Taeno waterfall site was determined based on field measurements of elevation difference between the proposed intake location and turbine installation point. The gross head was measured as **24 m**.

Gross head is defined as:

$$H_{gross} = Z_{intake} - Z_{turbine}$$

Where:
- H_{gross} = gross head (m)
- Z_{intake} = intake elevation (m)

- $Z_{turbine}$ = turbine elevation (m)

(ESMAP, 2019)

However, the effective head available for power generation is reduced due to friction losses and minor losses along the penstock. Therefore, net head must be calculated.

Penstock Design Parameters
The proposed penstock specifications are presented in Table X.

Table 7. Penstock Design Parameters

Parameter	Value
Gross head	24 m
Penstock length	26 m
Horizontal length	10 m
Design discharge	0.35 m³/s
Pipe material	Steel
Number of bends	7
Number of valves	3
Installation type	Supported

Penstock Diameter Selection
The pipe diameter was determined based on allowable flow velocity. Recommended velocities for micro hydropower steel penstocks typically range between 2–4 m/s (World Bank, 2016).

Using the continuity equation:

$$Q = AV$$

$$D = \sqrt{\frac{4Q}{\pi V}}$$

Assuming design velocity $V = 3\, m/s$:

$$D \approx 0.39\, m$$

Thus, a practical commercial pipe diameter of **400 mm** was selected.
The resulting flow velocity is:

$$V = \frac{Q}{A} = 2.78\, m/s$$

This value falls within the recommended range for steel penstocks.

Friction Loss Calculation
Head loss due to pipe friction was calculated using the Darcy–Weisbach equation:

$$h_f = f\frac{L}{D}\frac{V^2}{2g}$$

Where:
- h_f = friction loss (m)

- f = friction factor (0.02 for steel pipe)
- L = pipe length (m)
- D = pipe diameter (m)
- V = flow velocity (m/s)

(Subramanya, 2013)

The calculated friction loss is:

$h_f \approx 0.50 \, m$

Minor Loss Calculation

Minor losses caused by bends and valves were estimated using:

$$h_m = K \frac{V^2}{2g}$$

Where:

- K = loss coefficient

Typical coefficients:

- Bend = 0.3 each
- Valve = 0.2 each

Total loss coefficient:

$K = (7 \times 0.3) + (3 \times 0.2) = 2.7$

Thus:

$h_m \approx 1.06 \, m$

Net Head Calculation

Total head loss:

$h_{loss} = h_f + h_m = 1.56 \, m$

Net head is therefore:

$H_{net} = H_{gross} - h_{loss}$
$H_{net} \approx 22.44 \, m$

The net head represents approximately **93.5% efficiency** relative to the gross head, which is considered very good for micro hydropower systems.

The hydraulic analysis indicates that the Taeno site possesses favorable head conditions for micro hydropower development. The relatively short penstock length (26 m) and moderate number of fittings result in low hydraulic losses, allowing most of the available head to be utilized for power generation.

The selected pipe diameter of 400 mm provides an optimal balance between construction cost and hydraulic efficiency. Larger diameters would reduce head loss slightly but significantly increase material cost, while smaller diameters would increase friction losses and reduce net head.

Supported pipe installation is appropriate for the steep terrain of the waterfall site because it simplifies construction and maintenance while reducing excavation requirements. However, structural supports must be designed to withstand internal pressure and environmental loads such as wind and vibration.

Overall, the calculated net head of approximately 22.44 m confirms that the site is suitable for micro hydropower installation, particularly for impulse or crossflow turbine configurations typically applied in medium-head conditions (Paish, 2002).

Micro Hydropower Potential
Design Parameters

The hydropower potential at the Taeno waterfall site was estimated using the design discharge obtained from dependable flow analysis and the net head calculated from the hydraulic head and penstock analysis. The design parameters used for power estimation are summarized in Table 8.

Table 8. Hydropower Design Parameters

Parameter	Value	Unit
Design discharge (Q80)	0.35	m³/s
Gross head	24	m
Net head	22.44	m
Water density (ρ)	1000	kg/m³
Gravitational acceleration (g)	9.81	m/s²
Overall efficiency (η)	0.75	—

The overall efficiency includes turbine efficiency, generator efficiency, and mechanical losses. Typical efficiency values for micro hydropower systems range between 60% and 85% depending on turbine type and operating conditions (ESMAP, 2019).

Theoretical Power Calculation

The theoretical hydropower potential was calculated using the standard hydropower equation:

$P = \rho g Q H \eta$

Where:
- P = electrical power output (W)
- ρ = water density (1000 kg/m³)
- g = gravitational acceleration (9.81 m/s²)
- Q = discharge (m³/s)
- H = net head (m)
- η = overall efficiency

(ESMAP, 2019; Paish, 2002)

Substituting the design values:

$P = 1000 \times 9.81 \times 0.35 \times 22.44 \times 0.75$

$P \approx 57,800 \text{ W}$

$P \approx 57.8 \text{ kW}$

Thus, the estimated electrical power output of the proposed micro hydropower system is approximately **58 kW**.

Based on international classification standards, hydropower systems are categorized as:

Table 9. Hydropower System Category (Paish, 2002)

Type	Capacity Range
Pico hydro	< 5 kW
Micro hydro	5 – 100 kW

Type	Capacity Range
Mini hydro	100 kW – 1 MW

The estimated capacity of 58 kW falls within the **micro hydropower** category (Paish, 2002).

Annual Energy Production

Annual energy production was estimated using:

$$E = P \times CF \times 8760$$

Where:

- E = annual energy (kWh/year)
- CF = capacity factor
- 8760 = hours/year

For run-of-river micro hydropower systems, capacity factors typically range between 40% and 70% depending on hydrological variability (World Bank, 2016). Assuming a conservative capacity factor of **60%**:

$$E = 57.8 \times 0.60 \times 8760$$

$$E \approx 303{,}000 \text{ kWh/year}$$

Therefore, the estimated annual energy production is approximately **303 MWh/year**.

The calculated hydropower potential demonstrates that the Taeno waterfall site possesses significant energy generation capability for small-scale renewable electricity production. The estimated capacity of approximately 58 kW is sufficient to supply electricity for tourism facilities, including lighting systems, kiosks, public infrastructure, and supporting services. Additionally, excess energy could potentially be utilized for nearby community electrification or battery storage systems.

Seasonal discharge variability may influence energy production throughout the year; however, dependable flow analysis indicates that sufficient water resources are available for continuous operation during most months. Integrating hybrid renewable energy sources such as solar photovoltaic systems could further enhance system reliability during low-flow periods.

Turbine Selection and System Configuration

Based on hydraulic conditions, economic considerations, maintenance requirements, and system capacity, the **crossflow turbine** is identified as the most suitable option for the Taeno micro hydropower project.

The main reasons include:

1. Compatibility with medium head (22.44 m) and moderate flow (0.35 m³/s)
2. High efficiency across varying discharge conditions
3. Simple construction suitable for local fabrication
4. Lower cost compared with impulse and reaction turbines
5. Ease of operation and maintenance in remote locations

These characteristics make crossflow turbines particularly appropriate for decentralized renewable energy systems in developing regions (Williams & Simpson, 2009).

Expected Turbine Performance

Typical efficiency values for crossflow turbines range between **70% and 85%**, depending on design quality and operating conditions (ESMAP, 2019). Assuming an overall system efficiency of 75%, the estimated power output of approximately 58 kW is achievable under design flow conditions.

The turbine selection analysis confirms that the Taeno waterfall site is well suited for medium-head micro hydropower technology. The selection of a crossflow turbine provides an optimal balance between performance, cost, and reliability, which is particularly important for sustainable tourism electrification projects in remote regions.

Furthermore, the crossflow turbine's ability to operate efficiently under partial flow conditions enhances system resilience during seasonal discharge variations. This operational flexibility is advantageous for run-of-river systems where flow conditions change throughout the year.

Techno-Economic Analysis
Electricity Demand Estimation for Tourism Facilities
Electricity consumption in nature-based tourism destinations typically includes lighting, small commercial activities, visitor facilities, communication equipment, and water supply systems. Previous studies on rural tourism electrification indicate that small tourism facilities such as eco-lodges, visitor centers, and recreational areas typically require between **20 kW and 80 kW** depending on scale and visitor intensity (Becken & Simmons, 2012; UNWTO, 2018).

For locations similar to Taeno Waterfall, electricity demand generally includes:
- Pathway and decorative lighting
- Food stalls and kiosks
- Charging stations
- Water pumps
- Toilets and sanitation facilities
- Small administrative buildings
- Security lighting

Based on comparable tourism sites reported in the literature, the estimated electricity demand for Taeno Waterfall was developed as shown in Table X.

Table 10. Estimated Electricity Demand for Taeno Waterfall Tourism Area

Load Component	Unit Power (W)	Quantity	Total Power (kW)	Operating Hours (h/day)
Lighting systems	50	120	6.0	8
Food stalls	800	10	8.0	6
Charging stations	200	20	4.0	6
Water pump	1500	2	3.0	3
Public facilities	2000	1	2.0	8
Administration building	3000	1	3.0	8
Miscellaneous loads	—	—	4.0	6
Total Peak Load			**30 kW**	

Daily and Annual Energy Demand
Daily energy consumption was calculated using:
$E = P \times t$
Where:
- E = energy (kWh)

- $P=$ power (kW)
- $t=$ operating time (hours)

The estimated daily energy consumption is:

$$E_{daily} \approx 180 \text{ kWh/day}$$

Annual demand:

$$E_{annual} = 180 \times 365$$
$$E_{annual} \approx 65,700 \text{ kWh/year}$$

Thus, the tourism site requires approximately **66 MWh/year**, which is significantly lower than the estimated hydropower production capacity (303 MWh/year).

This indicates that the micro hydropower system can fully meet the tourism electricity demand with substantial energy surplus for future expansion or nearby community electrification.

Economic Feasibility Analysis
Revenue Estimation
The economic feasibility analysis was conducted using the average Indonesian electricity tariff for residential consumers, approximately **0.086 USD/kWh**, equivalent to IDR 1,444.7/kWh. This value represents the national electricity price regulated by the state utility company (PLN) and is commonly used as a benchmark for renewable energy feasibility studies in Indonesia (ESDM, 2023).

Annual electricity revenue based on generated energy:
$Revenue \approx 26,058 \text{ USD/year}$

Investment Cost Estimation
Typical micro hydropower installation costs range between **2000–4000 USD/kW** depending on site conditions and civil works requirements (ESMAP, 2019).

Assuming a conservative cost of:

3000 USD/kW

Total investment cost:
$Cost = 58 \times 3000$
$Cost \approx 174,000 \text{ USD}$
Including transportation and contingency (30%):
$Total \approx 226,000 \text{ USD}$

Operation and Maintenance Cost
Annual operation and maintenance (O&M) costs for micro hydropower systems typically range from **2%–5% of capital cost** (World Bank, 2016).
Assuming 3%:
$O\&M \approx 6,780 \text{ USD/year}$

Net Annual Benefit
$Net\ Benefit = 26,058 - 6,780$
$Net\ Benefit \approx 19,278 \text{ USD/year}$

Payback Period

$$Payback = \frac{Investment}{Annual\ Benefit}$$

Payback≈11.7 years

Thus, the estimated payback period is approximately **12 years**.

Levelized Cost of Energy (LCOE)

LCOE was estimated using:

$$LCOE = \frac{total\ lifetime\ cost}{total\ energy}$$

Assuming:
- Lifetime = 20 years
- Discount rate = 8%

The estimated LCOE is approximately:

$LCOE \approx$ 0.07–0.10 USD/kWh

This value is comparable to the Indonesian grid tariff, indicating that the project is economically feasible, particularly when considering non-financial benefits such as energy independence, tourism development, and environmental sustainability.

The economic analysis shows that the micro hydropower project at Taeno Waterfall is financially viable under realistic Indonesian electricity pricing conditions. The investment still falls within the acceptable range for renewable energy infrastructure projects, which typically exhibit long lifetimes exceeding 20–25 years (Paish, 2002).

Additionally, several factors may improve economic performance, including:
- Increased tourism revenue due to improved facilities
- Government subsidies or grants
- Carbon emission reduction incentives
- Expansion of electricity supply to nearby communities

The micro hydropower system also offers advantages over diesel-based generation, including lower operational costs, reduced fuel dependency, and environmental benefits.

CONCLUSION

This study evaluated the technical and economic feasibility of micro hydropower development at Taeno Waterfall in Ambon, Indonesia, to support sustainable tourism electrification. Hydrological analysis using 10-year rainfall data (2014–2023) combined with the NRECA method demonstrated that the Taeno watershed possesses favorable water resource conditions, with an average annual rainfall of approximately 3619.92 mm/year and an estimated average discharge of 0.70 m³/s. Flow duration curve analysis produced dependable discharge values of Q50 = 0.63 m³/s, Q80 = 0.35 m³/s, and Q90 = 0.28 m³/s, indicating sufficient water availability to sustain micro hydropower operation throughout most of the year.

Hydraulic analysis showed that the site provides a gross head of 24 m with an estimated net head of 22.44 m after accounting for friction and minor losses in the penstock system. Using a design discharge of 0.35 m³/s and an overall system efficiency of 75%, the estimated electrical power output is approximately 58 kW, which falls within the micro hydropower classification. The relatively short penstock length and moderate hydraulic losses contribute to efficient energy conversion and favorable system performance.

Based on turbine selection analysis, a crossflow turbine was identified as the most suitable option for the site due to its compatibility with medium-head and moderate-flow conditions, relatively low cost, operational flexibility, and ease of maintenance. The crossflow turbine's ability to maintain efficiency under varying flow conditions is particularly advantageous for run-of-river micro hydropower systems in tropical regions with seasonal discharge variability.

Electricity demand estimation for tourism facilities comparable to Taeno Waterfall indicates a peak load of approximately 30 kW and an annual energy requirement of about 66 MWh. The proposed micro hydropower system, with an estimated annual production of 303 MWh, is therefore capable of fully meeting the tourism electricity demand while providing surplus energy for future expansion or nearby community electrification. This surplus capacity enhances system reliability and supports long-term development potential.

Economic feasibility analysis using the Indonesian electricity tariff of 0.086 USD/kWh indicates an annual electricity value of approximately 26,058 USD and a net annual benefit of about 19,278 USD after operation and maintenance costs. The estimated payback period is approximately 12 years, which is considered acceptable for renewable energy infrastructure with a lifespan exceeding 20 years. Economic performance may improve further when considering avoided diesel fuel costs, tourism revenue growth, or government renewable energy incentives.

Overall, the results demonstrate that Taeno Waterfall possesses strong technical and economic potential for micro hydropower development. The combination of adequate water resources, favorable hydraulic head, moderate investment cost, and sufficient electricity demand supports the feasibility of implementing a renewable energy system for sustainable tourism electrification. In addition to providing reliable electricity, the proposed system could enhance environmental sustainability, reduce greenhouse gas emissions, and strengthen the eco-tourism value of the destination.

Future research may focus on hybrid renewable energy integration, detailed environmental impact assessment, and community-based energy management models to further optimize system performance and sustainability outcomes. The findings of this study provide a useful reference for micro hydropower development in similar small island tourism environments across Indonesia and other tropical regions.

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NOMENKLATUR

Symbol	Description	Unit
A	Cross-sectional area of flow	m²
A_{ws}	Watershed area	m² or km²
B_t	Benefit in year t	USD
C	Runoff coefficient	—
CF	Capacity factor	—
C_t	Cost in year t	USD
D	Penstock diameter	m
E	Energy produced	kWh
E_{annual}	Annual energy production	kWh/year
ET	Evapotranspiration	mm
f	Darcy friction factor	—
g	Gravitational acceleration (9.81)	m/s²
GWF	Groundwater factor (NRECA parameter)	—
H	Hydraulic head	m
H_{gross}	Gross head	m
H_{net}	Net head	m
h_f	Friction head loss	m
h_m	Minor head loss	m
IRR	Internal rate of return	%
K	Minor loss coefficient	—
K_c	Crop coefficient	—
L	Penstock length	m
LCOE	Levelized cost of energy	USD/kWh
m	Rank order in flow duration analysis	—
n	Number of observations	—
NPV	Net present value	USD

N_s	Specific speed	—
O&M	Operation and maintenance cost	USD/year
P	Power output	W or kW
P_{avg}	Average rainfall	mm
P_i	Rainfall data for year i	mm
PSUB	Subsurface flow coefficient (NRECA parameter)	—
Q	Discharge (flow rate)	m³/s
Q_{avg}	Average discharge	m³/s
Q_{50}	Discharge exceeded 50% of time	m³/s
Q_{80}	Discharge exceeded 80% of time	m³/s
Q_{90}	Discharge exceeded 90% of time	m³/s
r	Discount rate	—
RO	Runoff depth	mm
Rtahunan	Annual rainfall	mm/year
SMSTOR	Soil moisture storage (NRECA parameter)	mm
t	Time	s or h
V	Flow velocity	m/s
Z	Elevation	m
ΔS	Change in storage	mm
ρ	Water density	kg/m³
η	Overall system efficiency	—