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Feasibility and sensitivity assessment of various heads for micro-hydropower plant design in the Deluwang watershed, Indonesia

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ABSTRACT

The escalating global demand for electrical energy, including in Indonesia, underscores the need for renewable energy sources like micro-hydropower plants (MHPs). This study examines the financial feasibility and sensitivity of MHP projects in the Deluwang watershed, Situbondo Regency, Indonesia. Three cases with varying head elevations and discharge rates were analyzed, utilizing crossflow turbines. Case 1, with the highest head and discharge, emerged as the most profitable, demonstrating the highest values for Net Present Value (NPV), Benefit–Cost Ratio (BCR), and Internal Rate of Return (IRR). The study found that on-grid systems, despite higher initial costs, offer more stable revenue and faster payback periods compared to off-grid systems. Sensitivity analysis revealed the on-grid method's resilience to fluctuations in interest rates, project lifespan, and river discharge, maintaining feasibility with up to an 80% reduction in discharge over 15 years. This highlights the importance of strategic planning in MHP design, considering head and discharge rates to optimize power generation. The findings provide valuable insights for renewable energy development, contributing to Indonesia's energy needs and local socio-economic benefits. Future research should further explore the socio-economic impacts of MHP installations to enhance their development and sustainability.

Key words: discharge, feasibility, head, micro-hydro, sensitivity analysis

HIGHLIGHTS

- The highest head and crossflow turbine, showed the best profitability and efficiency, achieving the highest NPV, BCR, and IRR.
- The on-grid method proved adaptable to changes in interest rates, MHP lifespan, and river discharge, offering a fast payback period.
- Optimal MHP performance relies on selecting the right head and flow rates, with higher heads significantly boosting turbine efficiency and energy output.

1. INTRODUCTION

The escalating demand for electrical energy, both presently and in the foreseeable future, poses a substantial challenge globally, including in countries such as Indonesia. To address this issue, there is a growing imperative to harness energy resources, particularly renewable sources, given their considerable potential. Among these, micro-hydropower plants (MHPs) emerge as a noteworthy alternative (Adeyeye *et al.* 2022), renowned for their eco-friendly characteristics (Deshamukhya & Choubey 2023). These systems utilize river discharge velocities at specific elevations to generate electricity, typically within the range of 5–100 kW (Albreem & Aspan 2018). The interplay between power, discharge, and headwater in MHP is inherently proportional, where increased velocity and elevation result in higher electrical energy production (Sasthav & Oladosu 2022). The

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criticality of this relationship underscores the need for strategic planning in selecting the appropriate head corresponding to the planned discharge, leveraging available flow data.

Despite the potential of micro-hydropower to address energy needs, the rural areas of Situbondo Regency, Indonesia, remain largely untapped. Specifically, the Deluwang watershed, as shown in Figure 1, harbors six identified potential hydropower locations. These locations were carefully chosen after thorough field validation. Notwithstanding the acknowledged potential, it is essential to underscore that the provision of an efficient micro-hydro setup presents a challenging facet for research (Hossain & Biswas 2023). Therefore, this article aims to examine the financial feasibility of planning an MHP and analyze the sensitivity with several parameters on Deluwang with different head and turbine types, coupled with a nuanced analysis of sensitivity encompassing various parameters, particularly focusing on Deluwang's distinct head and turbine types.

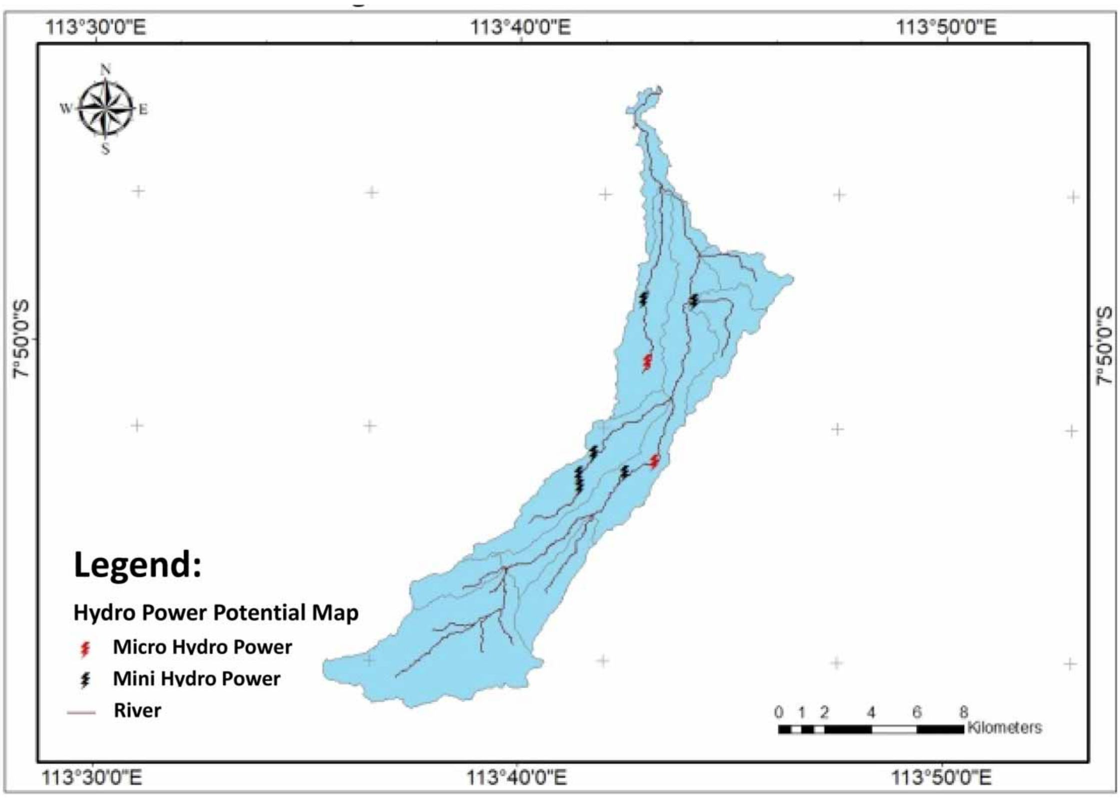

Figure 1 | Study area.

2. METHODOLOGY

2.1. Data and study area

Situbondo Regency is a city with several rivers that can be used as MHPs. Some of these rivers flow through coastal communities, taking advantage of the large river flow discharge to irrigate agricultural land and provide daily life needs from the weirs built along the river (Halik *et al.* 2022). Thus, this study explored one of the rivers, which is the Deluwang watershed in Situbondo District, East Java, as shown in Figure 1. The river has a discharge of 0.745 m^3/s and a head elevation of 19.28 m, a discharge of 0.547 m^3/s with a head elevation of 18.81 m, and a discharge of 0.589 m^3/s with a head elevation of 9.74 m.

2.2. Study cases

In this study, to find the potential for MHP planning, three cases were planned to be used to find the optimal potential for a power plant that has the most profit. For the representation of the cases, the following case data are explained in Table 1.

The cases are planned to determine which plan has the most potential to generate the most profit. The differences in each case are based on the location of the MHP, head elevation, and water flow rate, resulting in three

Table 1 | MHP design cases

Case	Location	Turbine	Discharge (m^3/s)	Head (m)	Turbine efficiency (%)
1	Deluwang 1	Crossflow	0.74463	19.28	87
2	Deluwang 2	Crossflow	0.54679	18.81	87
3	Deluwang 3	Crossflow	0.58914	9.74	87

cases to be analyzed. The best location for installing a hydroelectric system is determined by the available head and flow. Locations with a steady flow, a high head, proximity to end users, and security were all taken into account (Casila *et al.* 2019). Each case is assumed to be carried out for 15 years. The 15-year operational timeframe analyzed in this study corresponds with time frames frequently assessed in similar research, which offers an extensive perspective on long-term viability (Barroco 2021).

2.3. Method

The first step in analyzing the feasibility of planning an MHP was to calculate the annual energy production released by an MHP. The annual energy produced by a MHP can be calculated by the amount of electricity generated (kW) and the time required (T) for 1 year (8,760 h), which is deducted by assuming 24 days of maintenance per year (576 h). Thus, Equation (1) is used as follows to get energy per year multiplied by the price of electricity per kWh (Harvey 1993).

$$\text{Energy per year} = P \times (8,760 - T) \tag{1}$$

where P was the power generated by the MHP (kWh), and T was the maintenance time for the MHP components.

The next step was to design a budget for constructing an MHP based on three cases. MHPs have several components: intake, headrace, forebay, penstock, powerhouse, and tailrace. After calculating the planned cost budget based on three cases, we perform a cost flow analysis to determine how much profit will be obtained when this MHP operates per year. The annual yield can be found by calculating the power multiplied by the cost of goods sold.

A feasibility study with an operational length of 15 years can be carried out after knowing the benefits of the MHP operation. The four cases will be analyzed based on three parameters: NPV, BCR, and IRR, which then explore the sensitivity based on changes in interest rates, the age of the MHP, and river flow discharge.

2.3.1. Financial analysis

The definition of the component financial analysis is as follows:

- Cost flow (CF)

There are three main tasks for MHP construction that must be completed: civil works, mechanical works, electrical works, and network works for interconnection access. These four main tasks determine the number of investment costs or CF, which consists of four costs: the cost of procurement of goods (B1), civil building costs (B2), operational costs (B3), and transportation costs (B4). CF (Walz & Guenther 2021), can be expressed in Equations (2) and (3).

$$\mathrm{CF_0} = \mathrm{B1} + \mathrm{B2} + \mathrm{B3} + \mathrm{B4} \tag{2}$$

$$\mathrm{CF} = \mathrm{CF_0} + \text{Tax } 10\% \tag{3}$$

where $\mathrm{CF_0}$ is the cost flow before tax, and CF is the cost flow after tax. The tax used is 10% of the total planned budget.

- Cash inflow (CIF)

Cash inflow refers to the proceeds from selling electrical energy during the operation of the MHP, which was based on reliable discharge. Equation (1) is used to determine the energy produced in a year so that sales results can be known. The energy sales revenue (I) for 1 year (Akcay *et al.* 2017), is expressed in Equation (4).

$$\mathrm{CIF} = \mathrm{I} \times \text{Selling price per kWh} \tag{4}$$

where CIF is the cash inflow during the operation of the power plant, and I is the electrical energy generated for 1 year. The next step is calculating the annual cash inflow to find out the net income for 1 year of power plant operation.

- Annual cash inflow (A)

Annual cash inflow is the difference between income and cost. These costs include fixed costs (operational costs, maintenance costs, employee salaries, etc.) for 1 year of power plant operation. Equation (5) is used to determine the annual cash inflow (Akcay *et al.* 2017).

$$A = \text{CIF} - \text{Expenses per year} \tag{5}$$

where A is the annual cash inflow of the MHP which operates for 1 year, and CIF is the cash inflow.

2.3.2. Feasibility study

A feasibility study is a procedure for predicting the results of an examination or assessing a planned scheme by considering the benefits (Krieger *et al.* 2016). The main objective of a feasibility study is to evaluate technical, operational, and economic aspects. In this study, construction and implementation costs were considered. The feasibility analysis of MHP was carried out by preparing a discounted cash inflow with a value of 3.75% because the impact of time on all costs and benefits in the future must also be considered. The definition of the feasibility study is as follows:

- Net Present Value (NPV)

NPV is used to determine whether a project is feasible. Projects with positive values should be implemented, but those with negative values must be rejected. Because the NPV is positive, the combined present value of all cash inflows exceeds the present value of cash flows. Using Equation (6), the NPV value can be found (Hidayat *et al.* 2019).

$$\text{NPV} = \sum_{t=0}^{n} \frac{\text{NCF}_t}{(1+i)^t} \tag{6}$$

where NPV is the net present value ($), NCF_t is the net cash flow generated by the innovation project in year t, i is the discount rate (3.75%), and t is the year of investment. If the NPV is greater than 0, the decision criterion is accepted; if the NPV is less than 0, the project investment is rejected.

- Benefit–cost ratio (BCR)

The BCR is the ratio between income and costs incurred, showing the efficiency level in the use of capital. The BCR formula based on (Hidayat *et al.* 2019), is in Equation (7).

$$\text{BCR} = \frac{B_t}{C_t} \tag{7}$$

where B_t is the revenue earned in year t ($), and C_t is the cost incurred in the year ($). The decision criteria are that if BCR is greater than 1, the project investment is accepted. If the BCR is less than 1, the project investment is rejected.

- Internal Rate of Return (IRR)

IRR is the interest rate where the net present value of all cash flows (both positive and negative) from a project or investment equals zero [13]. The IRR formula based on [14], is in Equation (8).

$$\text{IRR} = i_1 + (i_2 - i_1)\frac{\text{NPV}^1}{\text{NPV}^1 - \text{NPV}^2} \tag{8}$$

where IRR is the internal rate of return, NPV is the net present value, i_1 is the interest rate that gives positive results (NPV^1), and i_2 is the interest rate showing negative results (NPV^2).

2.3.3. Sensitivity parameter

Sensitivity analysis evaluates the impact of changes in cost or benefit calculations on the feasibility of an investment or business activity. In this study, the sensitivity parameters include interest rate, project economic life, and flow rate. When analyzing sensitivity using these three parameters, the dynamic equation method can be applied to obtain solutions.

3. RESULTS AND DISCUSSION

3.1. Power of various cases

The MHP is expected to operate continuously for 1 year (8,760 h) but will be shut down for 2 days each month for maintenance, totaling approximately 576 h annually for repairs. Based on the three case information, as shown in Table 1, the power generated by the MHP is estimated using Equation (1), which is the result shown in Figure 2.

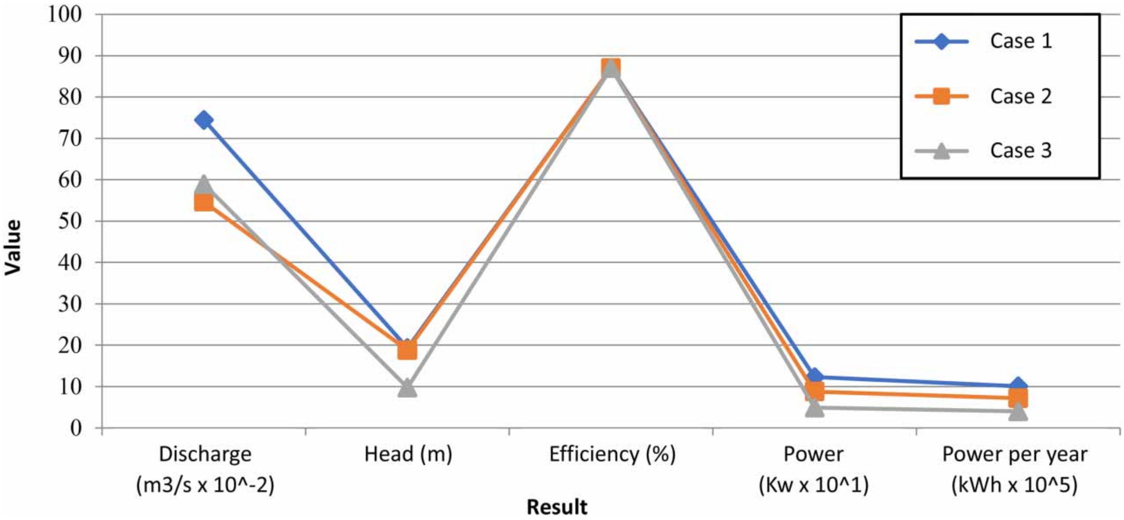

Figure 2 | MHP planning information.

Discharge and head elevation significantly affect the production of electrical energy. The electricity generated from the MHP will be calculated for the power released for 8,760 h, reduced by 576 h for maintenance annually. Based on Table 2, Case 3 produces the largest power, which is 13,230,228 kWh with a discharge of 0.546 m^3/s, head 18.81 m, and using a crossflow turbine. The significance of specific turbine types, discharge rates, and head elevations leads to optimal power generation (Ebrahimi *et al.* 2021). Compared to other types of hydropower turbines, the crossflow turbine is more suited for run-of-river and wave generation applications because its efficiency is primarily determined by flow rate (Elbatran *et al.* 2018).

Table 2 | Cost flow

Case	CF_0 ($)	Tax 10% ($)	CF ($)
1	67,199.95	6,719.99	73,919.94
2	63,663.56	6,366.36	70,029.91
3	63,663.56	6,366.36	70,029.91

3.2. Cost and benefit of different cases

3.2.1. Cost flow

The construction of the MHP in Deluwang is estimated to cost, as shown in Table 2.

There are differences in costs required for each case based on the MHP planning design. The most significant funding is for Case 1, planning at $73,919.94, which includes the procurement of goods, civil building costs, operational costs, and transportation costs.

3.2.2. Cash inflow

The cost of goods sold (COGS) for electrical energy reflects the expenses associated with the production and sale of electric power. For off-grid management, which refers to energy systems that operate independently from the main electrical grid, the cost is $0.0448 per kWh. Conversely, on-grid management involves connecting to the main electrical grid, allowing for the continuous supply of electricity without the need for local storage, resulting in a higher cost of $0.0643 per kWh due to transmission and distribution expenses. As a result, the price per kWh for electrical energy is shown in Table 3.

Table 3 | Expected cash flow

Case	Alternative	COGS ($/kWh)	*i* (kWh)	CIF (US $)
1	Off-grid	0.0448	1,004,995.2	45,023.78
	On-grid	0.0643	1,004,995.2	64,576.97
2	Off-grid	0.0448	718,391.52	32,183.94
	On-grid	0.0643	718,391.52	46,160.97
3	Off-grid	0.0448	400,770.48	17,954.52
	On-grid	0.0643	400,770.48	25,751.91

The calculation of profit per year shows that Case 1 (on-grid) has the most profit compared to other cases by generating a profit of $64,576.97, which is obtained from the power generated in 1 year and then sold for $0.0643 per kWh.

3.2.3. Annual cash inflow (A)

For determining A, expenditures consist of operational costs, maintenance, and taxes, which are assumed to be 10% of total annual revenue. The annual cash inflow that was estimated using Equation (5) is shown in Table 4.

Table 4 | Annual cash inflow

Case	Alternative	CIF (US $)	Maintenance and operation (US $)	Annual CIF (US $)
1	Off-grid	45,023.78	4,502.38	40,521.41
	On-grid	64,576.97	6,457.70	58,119.27
2	Off-grid	32,183.94	3,218.39	28,965.55
	On-grid	46,160.97	4,616.10	41,544.87
3	Off-grid	17,954.52	1,795.45	16,159.07
	On-grid	25,751.91	2,575.19	23,176.72

It is found that the case that produces the most net profit is Case 1 (on-grid) using a crossflow turbine at the location of Deluwang. Case 1 resulted in a net profit of $58,119.27. The results of the three cases will then be analyzed based on the feasibility of the NPV, BCR, and IRR. The cost flow analysis mirrors the challenges faced in the financial aspects of micro-hydro projects. The capital-intensive nature of micro-hydro development required the highest investment (Kishore *et al.* 2021), like in Case 1, Deluwang 1. Furthermore, grid connectivity plays an important role in maximizing revenue (Zhang *et al.* 2020), thus the high annual profit happens in Case 1 (on-grid).

3.3. Financial feasibility

3.3.1. Net Present Value

The operational length of the MHP is assumed to be 15 years. The feasibility analysis based on the NPV in the three cases is shown in Table 5.

Based on the calculations with the prevailing interest rate in Indonesia, namely, 3.75%, and the operating life of the MHP of 15 years, the most considerable NPV value is Case 1, with a value of $583,716.86. When viewed with the NPV parameter, the three cases are feasible to carry out for 15 years because they produce a value of more than 0.

3.3.2. The BCR

Equation (7) is used to find out how many BCR values are generated in each case that has been designed, as shown in Table 6.

Table 5 | The NPV

Case	Alternative	Annual cash inflow ($)	NPV ($)	Criteria	Feasibility
1	Off-grid	40,521.41	384,591.77	>0	Feasible
	On-grid	58,119.27	583,716.86	>0	Feasible
2	Off-grid	28,965.55	257,723.82	>0	Feasible
	On-grid	41,544.87	400,062.59	>0	Feasible
3	Off-grid	16,159.07	112,814.70	>0	Feasible
	On-grid	23,176.72	192,221.51	>0	Feasible

Table 6 | The BCR

Cases	Alternative	Cost ($)	Benefit ($)	BCR	Criteria	Feasibility
1	Off-grid	141,455.62	675,356.77	4.77	>1	Feasible
	On-grid	170,785.40	968,654.57	5.67	>1	Feasible
2	Off-grid	118,305.82	482,759.10	4.08	>1	Feasible
	On-grid	139,271.36	692,414.48	4.97	>1	Feasible
3	Off-grid	96,961.69	269,317.76	2.78	>1	Feasible
	On-grid	108,657.77	386,278.62	3.56	>1	Feasible

In all cases, the investment funds are less than the benefits. Case 1 has the highest BCR at 5.67, indicating that the MHP is feasible based on its present value.

3.3.3. Internal Rate of Return

The basis of the IRR value is the same as the interest rate, which makes the NPV value equal to zero. The project is viable if the IRR exceeds the current interest rate. Equation (8) is used to analyze the feasibility based on the IRR, which is shown in Table 7. The most considerable IRR value is in Case 1, which is 33.13%. By looking at the IRR value, which is more than the prevailing Indonesian interest rate of 3.75%, the project can be said to be feasible based on the IRR parameters.

Table 7 | The IRR

Case	Alternative	Annual CIF ($)	IRR (%)	Criteria	Feasibility
1	Off-grid	40,521.41	22,72	>3.75	Feasible
	On-grid	58,119.27	33,13	>3.75	Feasible
2	Off-grid	28,965.55	21,41	>3.75	Feasible
	On-grid	41,544.87	31,48	>3.75	Feasible
3	Off-grid	16,159.07	17,20	>3.75	Feasible
	On-grid	23,176.72	26,16	>3.75	Feasible

By changing the method between off-grid and on-grid, the results of NPV and IRR, which have the largest values are in Case 1, with the on-grid method having a relatively high BCR value of 5.67, as shown in Figure 3. The superior performance of the Case 1 on-grid method provides a safer investment and BCR value, resulting in huge profits in the future since grid connectivity enhances economic feasibility (Klein & Fox 2022).

3.4. Sensitivity analysis

Sensitivity analysis was conducted to determine the effect of changes in production parameters on changes in production system performance in generating profits. Sensitivity is analyzed based on different parameters, namely changes in interest rates, age changes, and discharge changes. The results of the sensitivity analysis are shown in Tables 8 and 9, and Figure 4.

The sensitivity analysis involving three parameters, it can be inferred that MHP planning in the on-grid scenario yields the most favorable outcomes when compared to all the other designed alternatives. Thus, on-grid

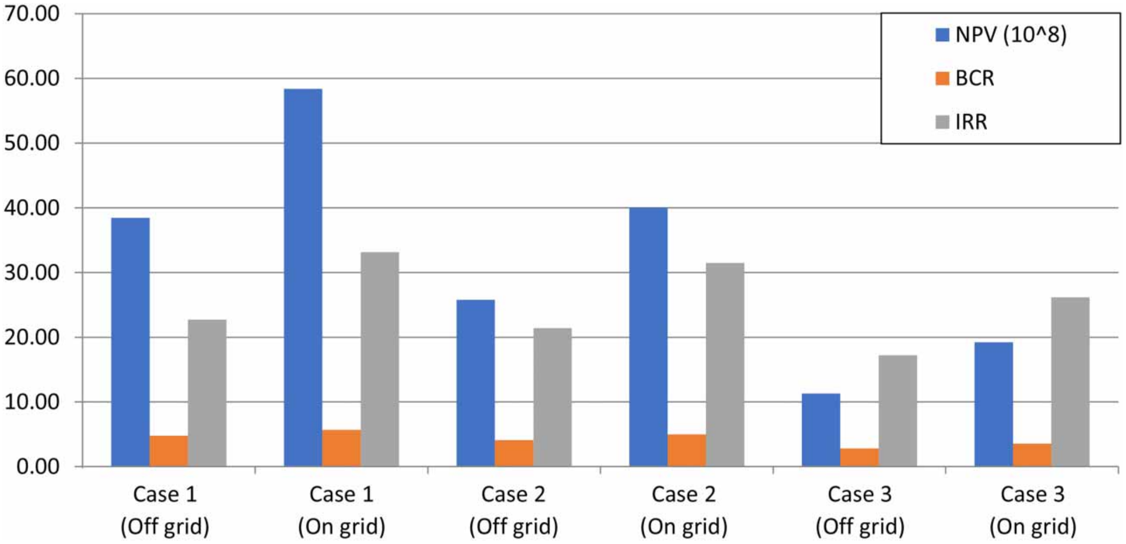

Figure 3 | The feasible parameter value.

Table 8 | Sensitivity analysis based on changes in interest rates

				NPV ($)			
Case	**Alternative**	**Investment ($)**	**Annual CIF ($)**	**Interest *r*. 18.75%**	**Interest *r*. 48.75%**	**Interest *r*. 78.75%**	**Interest *r*. max. (%)**
1	Off-grid	73,919.94	40,521.41	125,781.57	8,985.68	−22,472.66	54,73%
	On-grid	73,919.94	58,119.27	212,509.08	54,211.65	−129.83	78,61%
2	Off-grid	70,029.91	28,965.55	72,720.89	−10,767.24	−33,254.32	41,12%
	On-grid	70,029.91	41,544.87	134,715.52	14,969.69	−17,283.20	59,26%
3	Off-grid	70,029.91	16,159.07	9,606.76	−36,968.93	−49,513.84	21,88%
	On-grid	70,029.91	23,176.72	44,191.82	−22,611.02	−40,604.00	32,61%

Table 9 | Sensitivity analysis based on changes in the Deluwang flow rate

		NPV ($)				
Case	**Alternative**	**Decrease $Q = 10\%$**	**Decrease $Q = 30\%$**	**Decrease $Q = 50\%$**	**Decrease $Q = 70\%$**	**Decrease $Q = 90\%$**
1	Off-grid	307,800.17	222,973.48	138,146.79	25,296.46	−59,530.23
	On-grid	473,575.76	351,910.05	230,244.34	108,578.63	−13,087.09
2	Off-grid	202,781.44	142,156.70	81,531.95	−11,006.46	−71,631.21
	On-grid	321,259.52	234,306.31	147,353.10	60,399.90	−26,553.31
3	Off-grid	82,190.38	48,363.65	14,536.92	−51,203.48	−85,030.21
	On-grid	148,297.48	99,780.28	51,263.08	2,745.88	−45,771.31

proves to be the most adaptable to fluctuations in interest rates, MHP age, and river flow discharge. The maximum interest rate observed is 78.61%, allowing for a substantial decrease in discharge (80% below the planned discharge) while maintaining an operational period of at least 2 years to recover capital and generate a profit.

The profitability of MHP is significantly contingent on discharge, as shown in Figure 5. A higher river discharge corresponds to increased energy production, leading to greater profits from the sale of electrical energy. In selecting optimal outcomes, a key consideration is highlighted.

Technically, a higher head plays a pivotal role in enhancing power generation and turbine efficiency (Hoghooghi *et al.* 2018). However, from a financial standpoint, the magnitude of investment in MHP does not consistently correlate with more significant benefits or returns. It becomes evident that the adaptability of

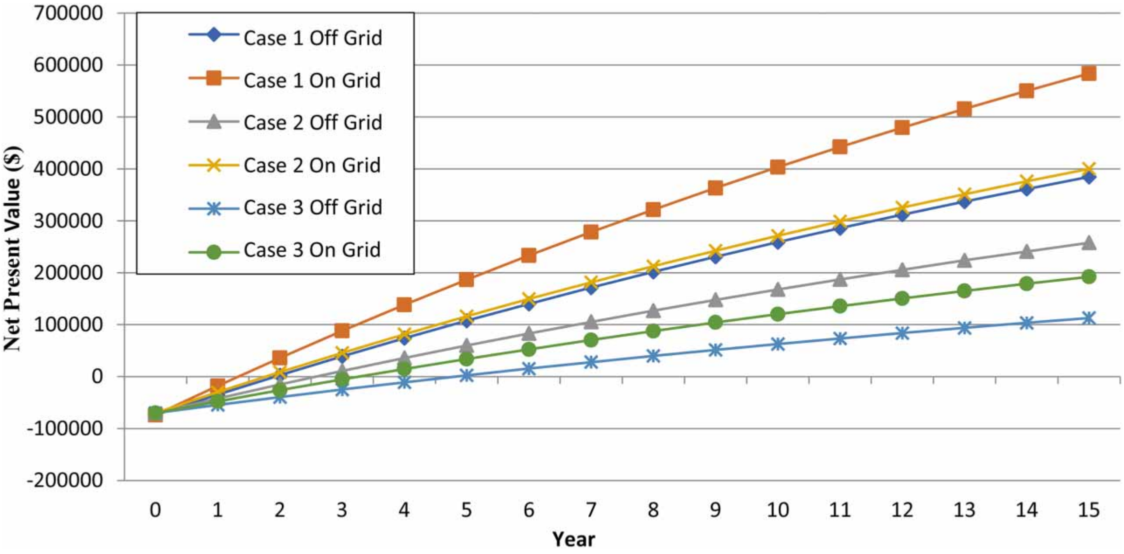

Figure 4 | Sensitivity analysis based on changes in the length of operation of the power plant (assumption 15 years).

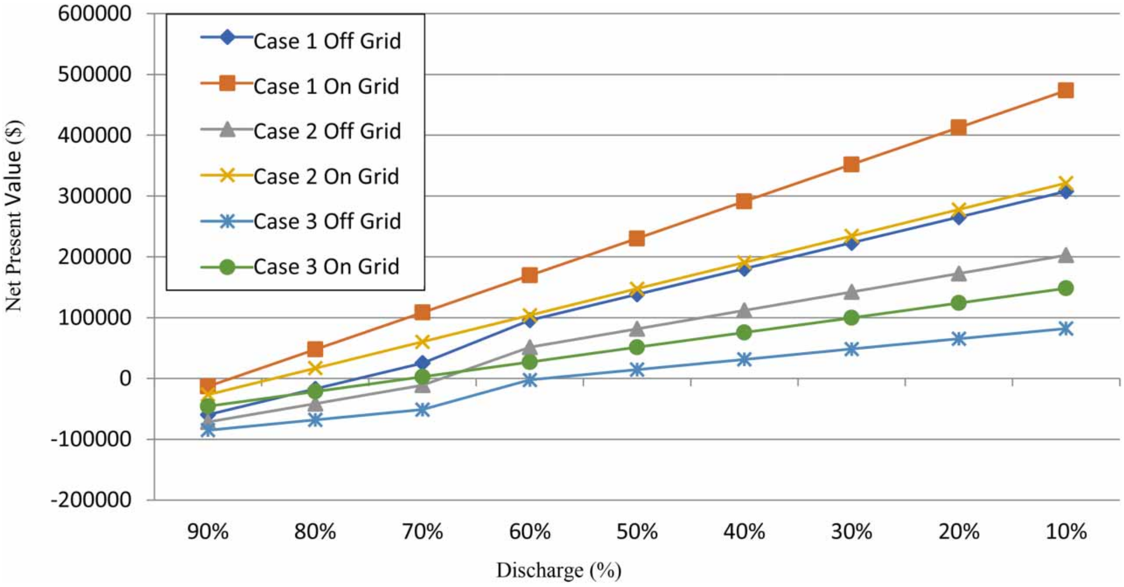

Figure 5 | Relationship between discharge versus the net present value within 15 years.

MHP during operations is tied to the level of profitability; the higher the profit, the better MHP can navigate changes in its operational dynamics (Ortiz-Partida *et al.* 2023).

3.5. Discussion

In addition to economic viability, the design and operation of an MHP must carefully consider technical issues, which are also related to the discharge, the head, and the grid connection system. The head directly influences the potential energy that can be converted into electricity, and a higher head typically results in more energy generation. This technical aspect is crucial because selecting the appropriate head for the MHP can optimize power generation, as shown in the Deluwang 1 case, where a higher head of 19.28 m, combined with a crossflow turbine, yields substantial electricity production. The higher heads significantly improve turbine efficiency and energy output (Ebrahimi *et al.* 2021), thus, they are critical for maximizing the return on investment in MHP projects. Interestingly, as highlighted in Table 1, a higher discharge, such as seen in Deluwang 3, does not necessarily correlate with a higher head compared to Deluwang 2. This phenomenon occurs because the geographical and topographical features of the riverbed and surrounding terrain dictate the head height. A higher discharge may be associated with a broader or less steep river section, resulting in a lower head despite the increased water volume. This balance is critical to ensuring the efficient conversion of hydraulic potential into electrical energy, and careful consideration must be given to both discharge and head in the design phase to optimize the MHP's performance (Walz & Guenther 2021).

Another critical technical factor is the discharge rate of the river, which affects the continuous supply of water required for optimal turbine operation. Fluctuations in river discharge can lead to variations in power output, impacting the overall efficiency and reliability of the MHP. Sensitivity analysis reveals that a reduction in discharge by up to 80% over 15 years still maintains feasibility, highlighting the importance of selecting a location with a consistent and reliable flow rate. The variability in the river flow must be managed carefully to sustain power generation and ensure economic feasibility (Moten & Thron 2013). In addition, the choice between an off-grid and an on-grid system plays a significant role. On-grid systems, which connect to the main electrical grid, offer more stable revenue due to the higher selling price of electricity and reduced costs related to storage and distribution. However, they require a more robust infrastructure and entail higher initial costs. In contrast, off-grid systems are more suitable for isolated areas where grid access is limited, although they pose challenges related to energy storage and consistent supply. Off-grid MHP systems, while essential for remote areas, require careful planning and substantial investment in storage solutions to ensure a steady energy supply (Casila *et al.* 2019).

4. CONCLUSIONS

There is significant potential for MHPs as a renewable energy source to meet Indonesia's growing electrical demand, focusing on the Deluwang watershed in Situbondo Regency. Among the three cases evaluated, Case 1, with its higher head elevation and crossflow turbine, emerged as the most profitable and efficient design, underscoring the importance of strategic planning in selecting optimal head and flow rates. The financial analysis confirmed the feasibility of the MHP projects, with Case 1 in the on-grid alternative showing the highest values for NPV, BCR, and IRR. Sensitivity analysis emphasized the adaptability of the on-grid method to interest rate fluctuations, MHP lifespan, and river discharge, and this alternative demonstrates the fastest payback period of approximately 2 years. The head and discharge rates have a critical role in optimizing power generation, with a higher head and crossflow turbine proving effective. While on-grid systems offer stable revenue due to higher selling prices of electricity, they also require robust infrastructure and higher initial costs. This includes investment in transmission lines and grid connection infrastructure, which can be technically challenging and financially demanding. This result provides valuable guidelines for optimal MHP design based on discharge and head availability, with successful implementation potentially contributing significantly to renewable energy production and socio-economic benefits for local communities. Future research should explore the socio-economic impact of MHP installations to enhance the development and sustainability of renewable energy projects.

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DATA AVAILABILITY STATEMENT

Data cannot be made publicly available; readers should contact the corresponding author for details.

CONFLICT OF INTEREST

The authors declare there is no conflict.

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