

Seasonal Water-Flow Risk and Business Sustainability in a Small-Scale Hydropower Enterprise: Evidence from Central Java, Indonesia

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Abstract

Fixed-tariff power purchase agreements (PPAs) give small-scale mini-hydropower plant (MHP) entrepreneurs in Indonesia price certainty, but not certainty over the volume of electricity they can sell. This study assesses the production and revenue vulnerability of an MHP enterprise to streamflow variability through a case study of the Pageruyung-1 MHP (2 MW, run-of-river) in Kendal Regency, Central Java. Recorded daily discharge for May 2023–August 2026 was used to estimate power output, simulate energy and the effective capacity factor (CF), and construct a monthly indicative revenue index; debt service capacity was analysed as a scenario. The lowest monthly mean discharge (431 L/s, October 2023) was only about one-third of the design discharge (1,311 L/s). Simulated annual CF ranged from 43% (May–December 2023) to 88% (2025), while monthly CF fell to as low as 33% in the dry season, below the 60% regulatory benchmark. In 2024, the revenue index of the lowest month was only 44% of that of the highest month (a 56% decline), with a coefficient of variation of 32%, compared with 18% in the wetter year of 2025. Under a level repayment scenario sized at an annual debt service coverage ratio (DSCR) of 1.3, the monthly DSCR in 2024 fell below 1.0 for six consecutive months (minimum 0.58); a repayment schedule sculpted to the seasonal pattern reduced this to four months. These findings indicate that the production and revenue vulnerability of MHPs should be assessed on the basis of the monthly distribution rather than annual averages, as a foundation for liquidity and financing planning by small-scale renewable energy entrepreneurs.

Keywords: Mini-hydropower; Sustainable entrepreneurship; Hydrological risk; Revenue volatility; Debt service coverage ratio; Feed-in tariff

1. Introduction

Indonesia's renewable energy policy provides price certainty to developers of small-scale mini-hydropower plants (MHPs) through power purchase agreements (PPAs). Under Regulation of the Minister of Energy and Mineral Resources (MEMR) No. 19 of 2015 and Presidential Regulation No. 112 of 2022, electricity tariffs are set according to the provisions in force throughout the contract term. This policy is aligned with the net-zero emission target for 2060 set out in Government Regulation No. 40 of 2025 on National Energy Policy. MEMR Regulation No. 19 of 2015 sets purchase prices without negotiation or escalation for a 20-year PPA term from the commercial operation date (COD), divided into two periods, years 1–10 and years 11–20, with the second-period tariff at approximately 62.5% of the first-period tariff. Nevertheless, price certainty does not automatically guarantee revenue certainty for mini-hydropower plants, because revenue is also determined by the volume of electricity that can be generated and sold. Hydropower production is strongly influenced by the availability and variability of river discharge, which is linked to rainfall patterns, drought, and changes in environmental conditions and land use in the watershed. Such hydrological variability can reduce electricity production and increase revenue uncertainty [1], [2].

In *run-of-river* systems, changes in discharge directly affect generation potential because hydropower output depends on discharge, head, and system efficiency. Although the power–discharge relationship can be assumed to be approximately linear when head and efficiency are relatively constant, turbine efficiency under actual operating conditions may vary with discharge [3]. Variability in water availability can in turn alter electricity production and revenue, creating financial risk for hydropower operators [4], [5]. Operation and maintenance costs, on the other hand, do not change in proportion to every change in discharge, yet they affect the NPV, IRR, and financial sustainability of the plant [6]. The combination of revenue fluctuations driven by discharge variability and relatively fixed operating costs makes the business sustainability of small-scale MHPs vulnerable, even though the selling

price is guaranteed by regulation. This calls for an assessment of the degree of business vulnerability of MHPs to changes in discharge and of its consequences for production and revenue stability.

The relationship between hydrology and hydropower performance has attracted considerable scholarly attention over the past five years. A systematic review by Adhikari *et al.* [7] of hydropower investments from 2018–2022 identified climate and hydrological risk as one of the most significant categories of investment risk, alongside environmental-anthropogenic and financial risks. At the technical-hydrological level, Garcia *et al.* [8] applied the SWAT+ model to 209 run-of-river small hydropower plants in Catalonia, Spain, and found that environmental flow requirements together with climate change could reduce the output of small plants by 27–78% relative to a business-as-usual scenario. At the macro level, Cuppari *et al.* [5] showed that the global drought in early 2023 reduced world hydropower output by 8.5%, with declines of up to 20% in some countries, and proposed a financial risk-pooling scheme based on hydrometeorological indices for hydropower-dependent countries. Meanwhile, a bibliometric review by Duah *et al.* [9] of 918 MHP publications from 2014–2024 showed that Indonesia has been the largest contributor of MHP publications worldwide since 2018, yet most of this research focuses on turbine design, GIS-based site selection, and technical optimisation rather than on financial risk or business sustainability.

Although the literature above documents that hydrological variability can significantly reduce hydropower output, most of these studies operate at two levels of analysis that are removed from the reality of small-scale MHP entrepreneurs: a technical-hydrological level that stops at estimating production losses [8], or a macro-financial level that addresses the fiscal risk of countries or large utilities [5]. The bibliometric review [9] explicitly identifies knowledge gaps in the form of limited documentation of governance, ownership, and community financing models, and inconsistent reporting of project performance metrics (investment cost, utilisation rate, and annual energy yield) at the level of individual MHPs, gaps that are directly relevant to small-scale MHP entrepreneurs operating under fixed-tariff regimes such as Indonesia's. In other words, research that explicitly links the recorded daily discharge data of a single MHP enterprise with regulatory obligations (such as the minimum capacity factor threshold) to measure the revenue vulnerability of that enterprise as an entrepreneurial unit of analysis, rather than merely a technical or macro-fiscal unit, remains very limited.

This study addresses that gap by analysing recorded daily discharge data (rather than global hydrological model simulations) from a single MHP enterprise operating in Indonesia, the Pageruyung-1 MHP in Kendal Regency, Central Java, together with the tariff provisions and the minimum capacity factor benchmark in Indonesian regulations. Four quantities are distinguished consistently throughout: recorded discharge (the only measured variable), estimated power (derived from discharge), simulated energy (aggregated estimated power capped at installed capacity), and indicative revenue (expressed as an index). The study makes three contributions. First, empirically, it translates the hydrological variability of a single enterprise into operational indicators of business vulnerability: the position of the capacity factor relative to the regulatory threshold, the monthly revenue index and its volatility, and a monthly debt service coverage ratio (DSCR) scenario. Because these index-based indicators do not depend on exchange rate or tariff assumptions, they can be compared across years and across plants. Second, for the sustainable entrepreneurship literature, it shows that in nature-based renewable energy ventures, the natural system that is to be sustained [10] is not merely a non-economic goal but a direct determinant of cash flow and financing capacity. This extends the natural-resource-based view [11] to small-scale energy ventures in developing countries. Third, for the literature on SME resilience and financial management [12], [13], it situates hydrological variability within a compound risk context, comprising hydrological conditions, the watershed environment, competition for water use by local communities, and financial leverage, and derives from it testable liquidity and financing decisions. This entrepreneurial perspective remains rarely addressed in the MHP literature, which generally focuses on engineering and hydrological aspects [9], while research on renewable energy entrepreneurship in Indonesia has focused on support mechanisms such as incubation, training, and capital support rather than on the operating cash-flow risk of individual ventures [14].

Accordingly, this study aims to (1) analyse the seasonal and inter-annual variability of discharge and estimated power output of the MHP; (2) assess the business vulnerability of the MHP to these discharge fluctuations using the capacity factor, a simulated revenue index, revenue volatility, and a monthly DSCR scenario; and (3) formulate business and managerial implications for the sustainability of small-scale hydropower enterprises in Indonesia, distinguishing implications directly supported by the results from those that remain conceptual.

2. Methods

2.1. Case Study and Data

This study adopts a single case study design with a quantitative-descriptive approach following the methodological framework of Yin [15], treating the case as the unit of analysis for understanding the links between hydrological conditions, generation performance, and business vulnerability. The case is used to illustrate risk patterns that are structurally relevant to the population of MHP developers in Indonesia operating under the same PPA scheme, not to produce statistical generalisations for all MHPs in Indonesia.

The object of study is the Pageruyung-1 MHP, a run-of-river plant with an installed capacity of 2 MW located on the Terong River, Blukar watershed, Gondoharum Village, Pageruyung District, Kendal Regency, Central Java, at an elevation of about 450 m above sea level with a gross head of 200 m. The plant characteristics used in the

analysis are summarised in **Table 1**. The plant began commercial operation (commercial operation date, COD) in May 2023 and sells electricity to PT. PLN, the state electricity company, under a PPA, falling within the capacity class of more than 1 MW up to 3 MW.

The research data comprise two groups. The first is the record of daily discharge (Q , L/s) logged directly by the plant operator, together with the estimated power output (P , kW) calculated by the operator from discharge using the actual operating parameters of the plant, namely a combined turbine-generator efficiency of 0.85, gravitational acceleration of 9.81 m/s^2 , and an effective head of 183 m, as well as a daily energy production column (kWh). The data cover May 2023 to August 2026, as shown in **Table 2**, comprising 245 days of valid data in 2023 (May–December, after COD), 366 days in 2024 (a full year), 365 days in 2025 (a full year), and 243 days in 2026 (January–August). Data for January–April 2023 are excluded because the plant had not yet reached COD (a pre-operation period, not a measurement gap), while the absence of data from September 2026 onwards is treated as data not yet available, not as zero production.

It should be noted that the directly measured variable is discharge; power (P) and energy in this study are theoretical estimates derived from discharge with a fixed efficiency of 0.85, not readings from the kWh meter for sales to PT. PLN. Consequently, daily P values can exceed the installed capacity (up to about 2,280 kW on high-flow days), so all energy and capacity factor calculations in this study cap daily power at 2,000 kW and assume 24-hour operation without downtime. In addition, parts of the record (more than 100 days, including early January 2024 and early January 2026) show linear patterns indicative of data infilling (interpolation), and the daily production column in some periods (e.g. 1–20 February 2025) is inconsistent with daily power; the production column was therefore not used, and energy was recalculated from capped daily power. The second group consists of regulatory and tariff data from MEMR Regulation No. 19 of 2015 (benchmark prices and location factors for hydropower ≤ 10 MW), Presidential Regulation No. 112 of 2022 (renewable energy ceiling prices and the minimum capacity factor requirement), and MEMR Regulation No. 4 of 2012 as historical context for small- and medium-scale renewable energy pricing schemes in Indonesia. The data recorded from May 2023 to August 2026 are presented in **Table 2**.

Table 1. Characteristics of the Pageruyung-1 MHP used in the analysis

Parameter	Value/specification
Location	Pageruyung District, Kendal Regency, Central Java
Coordinates of the permitted abstraction point	$7^{\circ}04' 06'' \text{ S}$; $110^{\circ}00' 07'' \text{ E}$
Water source	Terong River
Scheme; turbine type	Run-of-river; vertical-shaft Francis
Installed capacity (specification)	2,000 kW
Effective head	183 m
Maximum water abstraction (permit)	$2.7 \text{ m}^3/\text{s}$
Generator / transmission voltage	6.3 kV / 20 kV
Measurement point of P	Delivery side to the PT. PLN grid

Source: operator data and water resources permit documents.

Table 2. Monthly mean discharge of the Pageruyung-1 MHP (L/s), May 2023–August 2026

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2023	—	—	—	—	830	568	534	478	481	431	508	691
2024	1,385	1,402	1,337	1,336	1,067	787	679	651	607	571	730	969
2025	1,216	1,391	1,447	1,435	1,436	1,406	1,166	806	807	818	1,357	1,394
2026	1,358	1,304	1,356	1,342	1,337	854	547	526	—	—	—	—

Note: “—” indicates no data (2023: pre-COD period, January–April; 2026: no data recorded from September). Calculated from daily discharge data verified by the plant operator (245 days of data in 2023, 366 in 2024, 365 in 2025, and 243 in 2026).

2.2. Business Vulnerability Analysis Approach

The business vulnerability of the MHP to discharge supply was assessed through the following five quantitative steps. First, the design discharge was estimated using the hydropower equation given in Eq. (1).

$$P = 9.81 \times Q \times H \times \eta \quad (1)$$

where P is the power output (kW), Q is the discharge (m^3/s), H is the effective head (m), and η is the combined turbine-generator efficiency (dimensionless). The constant 9.81 is the product of gravitational acceleration (9.81 m/s^2) and water density ($1,000 \text{ kg/m}^3$) divided by 1,000, so that power is expressed directly in kW. Because discharge is recorded in L/s, values are divided by 1,000 before being entered into Equation (1). With an installed capacity of 2,000 kW, an effective head of 183 m, and an efficiency of 0.85, the parameters consistently used by the operator in its daily operating records, the design discharge is $2,000 / (9.81 \times 183 \times 0.85) \approx 1.311 \text{ m}^3/\text{s}$, or 1,311 L/s. This value is used consistently in all subsequent calculations.

Second, the effective capacity factor (CF) was simulated on a daily basis using Eq. (2), as the ratio of daily discharge to design discharge capped at 100%, and then averaged to obtain monthly and annual CF values (day-weighted). This formulation assumes a linear relationship between discharge and power when discharge is below the design discharge, and caps CF at 1.0 when discharge exceeds the design discharge because the installed capacity of the plant is only 2 MW. The calculation is performed daily rather than from monthly mean discharge because surplus flow on wet days cannot compensate for deficits on dry days within the same month.

$$CF_d = \min\left(\frac{Q_d}{Q_{design}}, 1\right) \quad (2)$$

where CF_d is the effective capacity factor on day d , Q_d is the recorded daily discharge on day d (L/s), Q_{design} is the design discharge (1,311 L/s), and $\min$ is the operator that selects the smaller of the discharge ratio and 1.

Third, the monthly revenue index was simulated. Monthly electricity generation was calculated using Equation (3), where E is the estimated monthly electricity generation (kWh), CF_{month} is the monthly capacity factor (the day-weighted mean of daily CF), $P_{installed}$ is the installed capacity (kW), and t is the number of hours in the month. In practice, Eq. (3) was computed as the sum of daily energy (daily CF $\times$ 2,000 kW $\times$ 24 h), which is equivalent to using the day-weighted monthly CF.

$$E = CF_{month} \times P_{installed} \times t \quad (3)$$

Because the PPA tariff is fixed without escalation throughout the first tariff period (years 1–8 from COD, which covers the entire observation period of this study since COD in May 2023), monthly revenue is directly proportional to simulated energy at the same tariff. This revenue is indicative because simulated energy does not account for downtime, losses, or auxiliary consumption. Monthly revenue is therefore expressed as an index rather than in a specific currency (rupiah or US dollars), to avoid dependence on exchange rate assumptions and to focus on the relative pattern of revenue volatility itself. The monthly revenue index is calculated using Eq. (4). A value of 100 represents a month with revenue equal to the annual average, values above 100 represent months with above-average revenue, and values below 100 represent months with below-average revenue.

$$\text{Monthly Revenue Index} = \frac{\text{Energy in the month}}{\text{Mean monthly energy in the same year}} \times 100 \quad (4)$$

Fourth, business vulnerability indicators. Vulnerability was assessed using three complementary measures: (a) compliance with the 60% minimum capacity factor threshold required by Article 18(1) of Presidential Regulation No. 112 of 2022 for run-of-river hydropower plants of up to 5 MW, used here as a benchmark; because this requirement is essentially evaluated annually, monthly CF is treated as an early indicator of the plant's position relative to the threshold rather than as a formal monthly compliance assessment; (b) the ratio and percentage decline in monthly revenue between the highest- and lowest-flow months within a year; and (c) the coefficient of variation (CV) of monthly revenue, i.e. the ratio of the standard deviation to the mean monthly revenue within a year, as a concise measure of the revenue volatility faced by the entrepreneur.

Fifth, debt service capacity scenario analysis. Because data on the plant's actual loan structure and operating costs are not available, the debt service coverage ratio (DSCR) is not calculated as an actual value but as a hypothetical scenario with all assumptions stated explicitly. Because the tariff is fixed, revenue, costs, and debt service are expressed in energy-equivalent units (MWh-equivalent), so that the tariff cancels out in the ratio. The monthly DSCR is calculated using Eq. (5).

$$DSCR_m = \frac{E_m - C_{OM}}{DS_m} \quad (5)$$

where $DSCR_m$ is the debt service coverage ratio in month m , E_m is the simulated energy in month m as a proxy for revenue at a fixed tariff, C_{OM} is the fixed monthly operation and maintenance cost, and DS_m is the debt service in month m . The base scenario uses the following assumptions: (i) debt service is sized so that the annual DSCR equals 1.3 against the mean monthly energy of 2024–2025 (1,166.9 MWh), a threshold set as a scenario assumption because lenders typically determine debt capacity and repayment schedules for renewable energy projects on the basis of a target DSCR [16]; (ii) fixed operation and maintenance costs equal 20% of average revenue (233.4 MWh-equivalent per month), with sensitivity tests at 15% and 30%; (iii) level monthly debt service of $(1,166.9 - 233.4) / 1.3 \approx 718.1$ MWh-equivalent; (iv) taxes, interest rate changes, and working capital changes are ignored; and (v) for the second tariff period (years 9–20), revenue is multiplied by 0.625 while operating costs and debt service are held constant. For comparison, a repayment schedule sculpted to the seasonal profile was also simulated, in which debt service in each calendar month is proportional to the mean operating cash flow of the same month in 2024–2025, with the same total annual debt service as the level schedule. Because this seasonal profile is derived from the same data, the results are illustrative (in-sample) rather than projections.

3. Results and Discussion

3.1. Results

3.1.1. Seasonal and inter-annual variability of discharge

Figure 1 shows that the monthly recorded discharge and estimated power output of the Pageruyung-1 MHP followed a clear seasonal pattern throughout May 2023–August 2026, peaking in the wet season (January–May) and reaching their lowest levels in the dry season (August–October). In 2024, the highest discharge was recorded in

February (1,402 L/s) and the lowest in October (571 L/s), with the wettest month carrying almost 2.5 times the discharge of the driest month. In 2025, the ratio between the wettest (March, 1,447 L/s) and driest (August, 806 L/s) months was about 1.8. The 2026 data show a sharp decline from June (854 L/s) to 547 L/s in July and 526 L/s in August, falling to about 40% of the design discharge, a level comparable to the 2023 minimum. The lowest point over the entire observation period was recorded in October 2023 (431 L/s), only about one-third of the estimated design discharge (1,311 L/s). This pattern reinforces the central argument of this study: in run-of-river systems such as the Pageruyung-1 MHP, price certainty under the PPA does not automatically guarantee certainty over the volume of energy that can be sold, because the plant has no meaningful storage capacity to buffer seasonal discharge fluctuations.

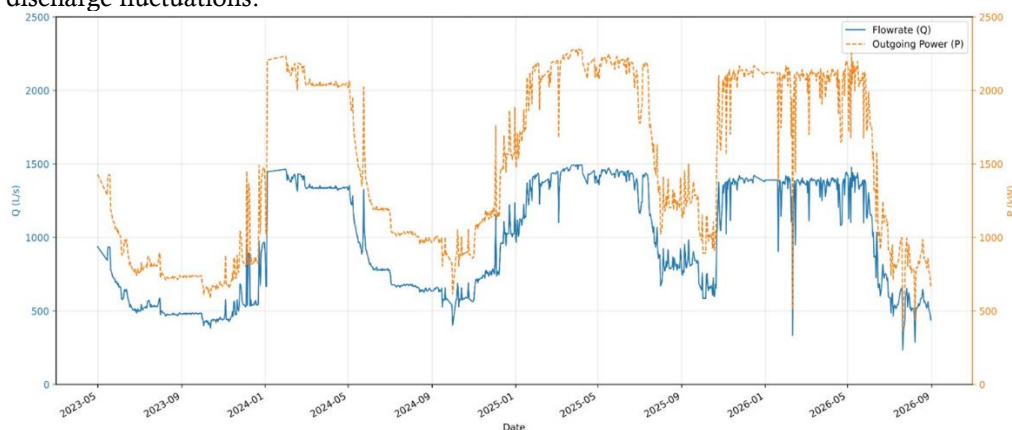


Figure 1. Recorded discharge (Q) and estimated power output (P) of the Pageruyung-1 MHP, May 2023–August 2026

3.1.2. Capacity factor and the regulatory threshold

Table 3 presents the monthly effective capacity factor (CF) of the Pageruyung-1 MHP. CF was calculated daily based on a design discharge of 1,311 L/s, a head of 183 m, and an efficiency of 0.85, capped at 100%, and then averaged by month.

Table 3. Simulated effective capacity factor (%), capped at 100%

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Average
2023 ¹	–	–	–	–	63	43	41	36	37	33	39	53	≈43%
2024	96	100	100	100	81	60	52	50	46	44	56	74	≈71%
2025	91	100	99	100	100	100	87	61	62	62	99	100	≈88%
2026 ²	99	95	99	98	97	65	42	40	–	–	–	–	≈79%

Note: ¹ Calculated from 245 operating days (May–December 2023). ² Calculated from January–August 2026 only (243 days). Annual averages are day-weighted rather than simple averages of monthly values.

The average CF in the first year of operation (2023) was only about 43%, with a low of 33% in October. This is well below the 60% minimum threshold required by Article 18(1) of Presidential Regulation No. 112 of 2022 for run-of-river hydropower plants of up to 5 MW. Almost all operating months in 2023 (seven of eight, all except May) fell below this threshold. In 2024, compliance improved but remained fragile: the capacity factor reached or approached 100% in February–April, but sat exactly at the threshold in June (60%) and then fell below 60% for five consecutive months (July to November), with a low of 44% in October. In contrast, 2025 showed full compliance throughout the year, and even the driest months (August–October) remained just above the threshold (61–62%). This pattern was disrupted again in 2026: after the first five months of the year remained consistently in the 95–99% range, the capacity factor dropped to 42% in July and 40% in August. This indicates that the risk of failing to meet the regulatory minimum capacity factor is recurrent: its timing is relatively predictable (the dry season), but its magnitude cannot be predicted from one year to the next. It is not a problem that resolves as the plant “matures” operationally, but a structural risk that can re-emerge at any time depending on the hydrological conditions of the current year.

3.1.3. Simulated monthly revenue and volatility as measures of vulnerability

The indicative revenue index was simulated for the entire observation period (May 2023–August 2026), with 2024, the first full calendar year (366 days), used as the main reference for discussion. Monthly energy was calculated from daily power capped at installed capacity and expressed as an index relative to the mean monthly energy of the same year (= 100), as presented in **Table 4**. The highest revenue index occurred in March (142.3), while the lowest occurred in October (62.1), only about 44% of the highest value, i.e. a decline of up to 56% within the same calendar year. As a more concise measure of vulnerability, the CV of the 2024 monthly revenue index was 32% around the mean of 100. By comparison, the same simulation for 2025, a year with generally higher discharge, yielded a much lower CV (18%) and a more favourable lowest-to-highest index ratio (≈60%, September compared with May). A similar pattern appears in the partial years: in January–August 2026, the index fell from 127.8 in March to 51.7 in August (a ratio of about 40%) with a CV of about 33%, while in May–December 2023 the lowest index (October, 77.1) was about 52% of the highest (May, 148.5) with a CV of about 24%. Because the averages for these two partial years cover only the available months, these figures are read as indications of the pattern rather than direct comparisons with 2024 and 2025. Because the CV and these ratios are relative measures (without

currency units), comparisons across years and across plants remain consistent without depending on exchange rate or tariff assumptions. The comparison shows that the level of revenue vulnerability of the MHP is not constant from year to year but follows the hydrological conditions of the current year, so that a business that appears relatively stable in one year (2025) can again become highly vulnerable in the following year (see the July–August 2026 pattern in **Table 3**). A CV of 32% in 2024 is high for the operating cash flow of a small business and confirms that feasibility analyses based solely on average annual revenue can conceal the real cash flow pressure faced by the entrepreneur in low-flow months.

Table 4. Simulated energy and monthly indicative revenue index of the Pageruyung-1 MHP, May 2023–August 2026 (monthly mean of the current year = 100)

Month	2023 ¹		2024		2025		2026 ²	
	Energy (MWh)	Index	Energy (MWh)	Index	Energy (MWh)	Index	Energy (MWh)	Index
January	–	–	1,425.2	136.3	1,352.7	105.0	1,466.4	127.0
February	–	–	1,392.0	133.1	1,340.9	104.1	1,281.7	111.0
March	–	–	1,488.0	142.3	1,480.2	114.9	1,475.6	127.8
April	–	–	1,440.0	137.7	1,440.0	111.8	1,409.1	122.0
May	942.0	148.5	1,208.4	115.6	1,488.0	115.5	1,449.1	125.5
June	623.9	98.3	864.5	82.7	1,434.9	111.4	938.7	81.3
July	606.4	95.6	771.1	73.8	1,288.3	100.0	621.4	53.8
August	542.5	85.5	738.8	70.7	914.7	71.0	597.0	51.7
September	528.5	83.3	667.2	63.8	886.2	68.8	–	–
October	489.4	77.1	648.8	62.1	924.5	71.8	–	–
November	558.0	88.0	801.8	76.7	1,422.0	110.4	–	–
December	784.4	123.6	1,100.5	105.3	1,488.0	115.5	–	–
Total (GWh)	≈5.08		≈12.55		≈15.46		≈9.24	
Monthly mean (MWh)	634.4 (= 100)		1,045.5 (= 100)		1,288.4 (= 100)		1,154.9 (= 100)	
Index CV (%)	24.2		31.7		18.4		32.9	
Lowest ÷ highest (%)	52.0 (Oct/May)		43.6 (Oct/Mar)		59.6 (Sep/May)		40.5 (Aug/Mar)	

Index = (energy in the month ÷ mean monthly energy in the same year) × 100. Energy was calculated from daily power capped at 2,000 kW, assuming 24-hour operation. ¹ May–December 2023 (after COD). ² January–August 2026. For 2023 and 2026, the mean is calculated only from the available months, so the indices and CVs for these two years are not fully comparable with those of full calendar years. Values above 100 indicate revenue above the current-year mean; values below 100 indicate revenue below the mean.

3.1.4. Asymmetry between discharge deficits and surpluses

Table 3 also shows that in 2025, five of the twelve months (February, April, May, June, and December) recorded a capacity factor of 100% and two others (March and November) approached 100%, i.e. when mean discharge exceeded or approached the estimated design discharge of 1,311 L/s. Because the installed capacity of the plant is limited to 2 MW, discharge above the design discharge does not generate additional energy or revenue in the simulation model. This produces an asymmetric risk profile: the entrepreneur bears the full economic impact when discharge falls below the design discharge but receives no comparable revenue compensation when discharge exceeds the design capacity. Such a payoff profile is structurally analogous to a position that bears downside risk without capturing the full upside, so MHP feasibility studies should explicitly consider the discharge distribution and the design capacity, not only the mean annual discharge.

3.1.5. Debt service coverage ratio (DSCR) scenario simulation

Table 5 presents the monthly DSCR from the scenario formulated in Equation (5). With level repayments, the annual DSCR for 2024 was 1.13, but the monthly DSCR fell below 1.0 for six consecutive months (June–November), with a low of 0.58 in October. In 2025, which appears healthy on an annual basis (DSCR 1.47), three dry-season months (August–October) still fell below 1.0. The number of deficit months did not change when the operating cost share was set at 15% or 30%. If the May–December 2023 pattern were to recur, the monthly DSCR would fall as low as 0.36 (October). The cumulative cash shortfall for debt service in 2024 was equivalent to about 1.7 times the monthly debt service, or 1.0 month of average revenue, compared with only about 0.2 times the monthly debt service in 2025. With a seasonally sculpted repayment schedule, without changing total annual debt service, the number of months with a DSCR below 1.0 in 2024 fell from six to four and the minimum rose from 0.58 to 0.84, while in 2025 all months remained above 1.25. In the second tariff period, a dry-season month with the October 2024 pattern would yield a DSCR of only about 0.24 if repayments were not adjusted.

Table 5. Monthly DSCR scenarios for the Pageruyung-1 MHP: level versus seasonally sculpted repayment, 2024–2025

Scheme / Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Annual
Level 2024	1.66	1.61	1.75	1.68	1.36	0.88	0.75	0.70	0.60	0.58	0.79	1.21	1.13
Level 2025	1.56	1.54	1.74	1.68	1.75	1.67	1.47	0.95	0.91	0.96	1.66	1.75	1.47
Sculpted 2024	1.34	1.33	1.30	1.30	1.14	0.90	0.88	1.11	1.04	0.98	0.84	1.06	1.13
Sculpted 2025	1.26	1.27	1.30	1.30	1.46	1.70	1.72	1.49	1.56	1.62	1.76	1.54	1.47

Note: DSCR = (monthly simulated energy – fixed O&M cost) ÷ monthly debt service, all in MWh-equivalent (Equation 5). Level schedule: debt service of 718.1 MWh-equivalent/month. Sculpted schedule: monthly debt service proportional to the mean operating cash flow of the same month in 2024–2025, with the same annual total. O&M cost: 233.4 MWh-equivalent/month. Values below 1.0 mean that operating cash flow in that month is insufficient to cover debt service. All values are scenario results, not actual DSCRs.

3.2. Discussion

3.2.1. Discharge as a variable shaped by environmental pressure

River discharge is driven not only by rainfall but also by land-use change, deforestation, and catchment degradation, which affect surface runoff, infiltration, and baseflow contribution. A study of the Bengawan Solo

watershed showed that land-use change and climate variability both contribute to changes in streamflow characteristics in Java [17]. A study of the Klambu Dam catchment in Central Java, the same province as the case site, documented a substantial reduction in forest cover alongside the expansion of agricultural land, which amplified changes in runoff timing [18]. Similar findings have been reported for the Cijung watershed [19] and for mountain deforestation in East Java, which has been linked to reduced dry-season water availability and increased water scarcity costs for downstream small-scale irrigation users [20]. These findings suggest that the discharge declines observed at the intake of the Pageruyung-1 MHP may reflect not only inter-annual rainfall variability but also structural pressure on the Blukar watershed that feeds it. However, this study does not yet have sufficient spatial and temporal land-use data to establish this causal relationship directly; watershed degradation is therefore positioned as a literature-supported risk factor, not as a cause that has been causally demonstrated at this site.

Beyond environmental pressure, water availability for the plant is also constrained by regulatory obligations. The water use permit for the Terong River for the Pageruyung MHP requires that plant operations do not disrupt the river's maintenance flow. The permit also requires the developer to release a maintenance flow of at least 0.30 m³/s (300 L/s) in dry months. This maintenance flow is equivalent to about 23% of the design discharge (1,311 L/s). Its share is much larger at the peak of the dry season, when monthly mean discharge falls to about one-third of the design discharge (≈ 0.44 m³/s). This obligation is asymmetric with respect to business risk and is most binding precisely in the months when the CF and revenue of the plant are already at their lowest. Findings from 209 *run-of-river* small hydropower plants in Catalonia show that *environmental flow* requirements, together with climate change, can substantially reduce the output of small plants [8]. The maintenance flow should therefore be treated as the first claim on river water in production and cash flow planning, not as a residual after the plant's needs are met. Compliance with this requirement is also part of the plant's social legitimacy and of the long-term sustainability of its operating permit.

3.2.2. Groundwater exploitation and competition for communal water use

In addition to surface water abstraction, groundwater exploitation within the watershed can also reduce river discharge, particularly in the dry season. In run-of-river systems, dry-season discharge is largely sustained by baseflow, i.e. the release of groundwater into the river channel. When the water table falls because of pumping, groundwater flow towards the river can decrease, reverse, or stop altogether, reducing river discharge. Globally, environmental flow limits are projected to be exceeded in about 42–79% of watersheds with groundwater pumping by 2050, generally before substantial groundwater storage losses are observed [21]. This phenomenon, known as streamflow depletion, is difficult to observe directly from discharge data, because the decline in discharge is attenuated and delayed relative to pumping, the volume and timing of groundwater abstraction are rarely recorded, and its effects are masked by weather variability and other factors [22]. Its estimation therefore requires analytical, numerical, or statistical models, with the choice of method depending on the management objective, namely attribution, impact, or mitigation [23]. Evidence from Java shows that this mechanism is locally relevant. In the Rejoso watershed, East Java, uncontrolled groundwater use for rice fields has reduced the flow of artesian springs that supply urban drinking water. A water balance analysis attributed the decline of about 30% in spring discharge over recent decades to upstream land degradation (47%) and groundwater abstraction in the lowlands (53%) [24]. For the Pageruyung-1 MHP, the implications are twofold. First, boreholes for household, irrigation, or commercial use within the Blukar watershed, if present, could reduce the baseflow that sustains dry-season discharge, which is precisely when the plant's capacity factor is already at its lowest. Second, because the effects of pumping are delayed, baseflow decline may proceed slowly and may not yet be visible in a three-year discharge record. This risk is therefore better treated as a long-term risk to the economic life of the PPA than as part of seasonal fluctuation.

Another non-climatic factor that may affect discharge is competing abstraction for domestic needs. The Community-Based Drinking Water Supply and Sanitation Programme (PAMSIMAS) has developed communal water supply systems in thousands of villages in Indonesia, including through the use of springs and upstream river reaches [25]. System dynamics modelling shows that communal water abstraction interacts with watershed recharge processes and upstream land-use conditions [26], while source reliability remains an operational challenge for the sustainability of PAMSIMAS systems [27]. If communal abstraction points are located upstream of the MHP intake within the same watershed, such abstraction could in theory reduce the residual discharge available to the plant, particularly in the dry season when domestic demand and hydrological scarcity peak together, a pattern consistent with the international literature on inter-sectoral competition for water [28], [29], [30]. However, this study does not yet include data on the location, volume, and timing of communal groundwater or surface water abstraction specific to the Blukar watershed. Consequently, the direct effect of these two factors on discharge decline at the Pageruyung-1 MHP cannot yet be established. Verification would require a field inventory of boreholes and abstraction points and monitoring of groundwater levels around the river channel.

3.2.3. Price certainty, volume uncertainty, and fixed debt service

A fixed-tariff PPA transfers price risk to PT. PLN, but the developer bears all of the volume risk. This risk becomes critical when the MHP is financed by a bank loan with fixed instalments, the typical financing route for small entrepreneurs without access to public capital markets. Hydropower investment is capital-intensive up front and is generally repaid through constant instalments, so a sufficiently large fall in revenue can erode the ability to meet debt obligations [5]. Debt service and operation and maintenance costs must be paid regardless of hydrological conditions, and credit rating agencies treat hydrological risk, particularly drought, as a factor that makes the

financial performance of hydropower producers volatile [38]. Within the framework of operating and financial leverage, the combination of relatively fixed operating costs [6] and fixed debt obligations amplifies swings in net income when revenue fluctuates [31], [32].

Lenders generally determine debt capacity and repayment schedules on the basis of the DSCR, and the design of the repayment schedule, not merely the tariff structure, is an important determinant of a project's exposure to cash flow shortfalls [16]. However, the DSCR in feasibility studies is usually calculated annually, whereas debt service is paid monthly. The scenario results in Table 5 show the consequence: annual DSCRs that appear adequate (1.13 in 2024 and 1.47 in 2025) conceal six and three consecutive months, respectively, in which operating cash flow is insufficient to cover debt service. In other words, default risk in run-of-river MHPs is seasonal and its timing is relatively predictable, so it can be anticipated through financing design.

The inter-annual dimension and the tariff structure aggravate this problem. A debt structure sized on wet-year data will exceed repayment capacity in dry years, while high cash flow volatility increases exposure to liquidity and refinancing risk [33]. Even for large hydropower utilities, strategies that rely mainly on reserve funds can force a utility to take on significant debt during severe droughts, and therefore need to be combined with index-based financial instruments [39]. Moreover, MEMR Regulation No. 19 of 2015 reduces the tariff from year 9 to an index of 62.5. If the loan tenor extends beyond the first tariff period without adjusting debt service, a dry-season month with a pattern like October 2024 would yield a DSCR of only about 0.24 (assumption v in the Method section).

This vulnerability ultimately returns to the entrepreneur in the form of a higher cost of capital. Evidence from the U.S. municipal bond market shows that water stress is associated with higher bond yields, i.e. a higher cost of debt [40], while the cost of capital for renewable energy projects in developing countries is, on average, considerably higher than in industrialised countries [41]. Volume risk that is not quantified transparently tends to be translated by lenders into higher interest rates, shorter tenors, or larger equity shares. The business vulnerability of MHPs thus stems from a structural mismatch between fixed prices, variable volumes, and fixed debt. This mismatch is not captured by feasibility analyses that rely only on annual averages.

3.2.4. Business and entrepreneurial implications

From an entrepreneurial perspective, small-scale MHP ventures are a form of sustainable entrepreneurship, that is, entrepreneurial action that pursues economic opportunities while depending on, and having an interest in sustaining, the natural systems that support it [10]. The findings of this study show that, for MHPs, “what is to be sustained” (discharge and watershed health) is not merely a non-economic goal. It is a direct source of the enterprise's cash flow. Consequently, hydrological risk should be treated as a core business risk rather than a technical risk delegated to civil engineers. The SME resilience literature shows that small businesses are generally vulnerable and ill-prepared for weather-related shocks, with the main barriers lying in limited internal resources, managerial perceptions, and weak external institutional support [12]. For renewable energy ventures in Indonesia, these barriers are compounded by regulatory uncertainty, infrastructure limitations, and restricted access to suitable finance [14]. The following implications are therefore organised at two levels: the entrepreneur's internal decisions and the design of the surrounding financing ecosystem.

First, MHP feasibility studies should shift from average-based to distribution-based analysis. Reviews of hydropower investment risk rank climate and hydrological risk among the most significant risk categories [7], yet in practice feasibility studies are still largely built on mean annual discharge and installed capacity. The findings in Table 4 show why this approach is misleading. The year 2025 produced a monthly revenue CV of 18%, whereas 2024 and January–August 2026 exceeded 30%. Feasibility studies that happen to be based on wet-year data will systematically underestimate risk. Entrepreneurs and lenders should test feasibility using dry-year scenarios (e.g. the 2023 or 2024 patterns), monthly revenue volatility indicators, and the DSCR on a monthly rather than only an annual basis [16].

Second, liquidity management should be designed explicitly around the seasonal cycle. Research on SME cash holdings shows that small firms tend to target a certain level of cash because external financing is costly and cash reduces the likelihood of financial distress [13]. Firms with more volatile cash flows also face greater exposure to liquidity risk [33]. The data in this study allow the size of such cash reserves to be estimated concretely. In 2024, the cumulative revenue shortfall below the mean during June–November reached about 170 index points, equivalent to roughly 1.7 months of average revenue. In the wetter year of 2025, the figure was about 88 index points (≈ 0.9 months) for August–October. In 2026, the shortfall for June–August alone already reached about 113 index points. The DSCR scenario in Table 5 provides a stricter measure from the debt service perspective: the cash shortfall for debt service in 2024 was equivalent to about 1.7 times the monthly debt service. Cash reserves built from wet-season surpluses should therefore be equivalent to at least two months of average revenue. These reserves should be managed as a separate account that is not used for profit distribution or expansion.

Third, the financing structure should be aligned with the seasonal production profile. Experimental evidence from microfinance shows that debt contracts requiring rigid repayments can discourage productive investment. Providing a grace period has been shown to increase investment and long-run profits, although it also raises default risk [34]. For MHPs, the same principle can be applied through a repayment schedule sculpted to the cash flow pattern, with larger instalments in the wet season and smaller ones in the dry season, together with a debt service reserve account. The simulation in Table 5 shows that seasonal sculpting, without changing total annual debt service, reduces the number of deficit months in 2024 from six to four and eliminates all deficit months in 2025. This approach is consistent with the finding that repayment schedule design is an important determinant of the

exposure of renewable energy projects to cash flow shortfall risk [16]. Evidence from Indonesia's new and renewable energy startup ecosystem points in the same direction: capital support showed no significant direct effect on startup growth, which stakeholders attributed to funding that was delayed, rigidly administered, or poorly matched to the operating realities of renewable energy ventures, leading the authors to recommend staged financing aligned with the long development cycles of such ventures [14]. For entrepreneurs, the ability to present daily discharge data and monthly cash flow simulations such as those in this study is an important asset in negotiating a more suitable loan structure.

Fourth, residual hydrological risk can be transferred through index-based financial instruments. Research on hydropower shows that financial contracts based on hydrological indices can reduce a plant's exposure to water scarcity, particularly when the index is designed seasonally to reduce basis risk [35]. More recent research shows that the performance of parametric insurance for hydropower operators depends strongly on index design and contract type, and that collaboration between insurers and operators yields better designs than adversarial negotiation [36]. At the national level, risk pooling has been shown to reduce the cost of such protection substantially [5]. In Indonesia, parametric insurance products remain limited and their development has focused mainly on disaster and agricultural risks [42]; to the authors' knowledge, no product specifically covers the hydrological risk of MHPs. This represents a distinct entrepreneurial opportunity for insurers, financial institutions, or MHP developer associations to develop collective protection products based on the discharge data that every plant already records routinely.

Fifth, entrepreneurs could consider diversifying their generation sources to reduce dependence on a single resource. Solar and run-of-river hydropower can be complementary, with the degree of complementarity depending on local climatic characteristics [37]. In Central Java, the dry season that depresses discharge generally coincides with a period of higher solar irradiation, so hybridisation with solar PV on existing land and interconnection infrastructure could help stabilise production. This option nevertheless requires a separate technical study and alignment with the PPA provisions and applicable interconnection regulations.

Sixth, the watershed should be regarded as a strategic corporate asset rather than merely an object of social responsibility. The natural-resource-based view holds that a firm's competitive advantage is rooted in its relationship with the natural environment [11]. For MHPs, the sustainability of discharge is a prerequisite for the sustainability of revenue. Experience with payment for ecosystem services schemes in Indonesia and Asia, including those involving downstream water users and upstream farming communities, shows that such cooperation endures only if it is designed to be both fair and efficient for both parties [38]. A study in East Java also shows that mountain forest degradation imposes real economic costs on downstream water users [20]. Allocating funds to upstream conservation, vegetation planting in the catchment, and a coordination forum for water users in the Blukar watershed can therefore be positioned as an investment in protecting a productive asset, with a horizon commensurate with the economic life of the PPA.

These findings shift the entrepreneurial question from "Is the selling price guaranteed?" to "Can the business survive the worst dry season?". **Table 6** summarises the evidence base for each implication. The first three implications are directly supported by the recorded data and simulations in this study, whereas the fourth to sixth remain conceptual propositions derived from the literature. All implications are nonetheless derived from a single case study. Their effectiveness, particularly lenders' willingness to offer seasonal repayment structures and the feasibility of index-based insurance instruments in Indonesia, should be tested empirically in future research.

Table 6. Evidence base and implementation indicators for each business implication

Implication	Evidence base	Implementation indicators
1. Distribution-based feasibility	Directly supported by record- and model-based results (Tables 3–5)	Monthly revenue CV; number of months with CF < 60%; minimum monthly DSCR under dry-year scenarios (2023/2024 patterns)
2. Seasonal liquidity reserve	Supported by simulation (Tables 4 and 5)	Cash reserve ≥ 2 months of average revenue or ≥ 1.7 times monthly debt service; ratio of reserve to cumulative dry-season shortfall
3. Sculpted repayment and DSRA	Supported by scenario simulation (Table 5); lender willingness not yet tested	Number of months with DSCR < 1.0; minimum monthly DSCR; DSRA balance at the start of the dry season
4. Index-based instruments	Conceptual, based on the literature [32], [33], [5]	Correlation between discharge/rainfall index and revenue (basis risk); premium cost relative to reduction in revenue volatility
5. Hybridisation with solar PV	Conceptual, based on the literature [35]	Seasonal solar–hydro output correlation; increase in combined CF in dry-season months
6. Watershed conservation as asset investment	Conceptual; causal link between watershed degradation and discharge not yet demonstrated at the case site	Inter-annual dry-season discharge trend; conservation funding per MWh; vegetation cover in the catchment

4. Conclusion

This study shows that electricity price certainty under a PPA does not automatically guarantee certainty of production volume and revenue for mini-hydropower plants (MHPs). The findings are summarised at three levels of evidence. First, record-based results: the recorded daily discharge of the Pageruyung-1 MHP from May 2023 to

August 2026 shows a clear seasonal pattern, with a lowest monthly mean discharge of 431 L/s (October 2023), about one-third of the design discharge of 1,311 L/s, and a wettest-to-driest month discharge ratio of about 2.5 in 2024 and 1.8 in 2025.

Second, model-based results: with power and energy estimated from discharge, the annual effective capacity factor was about 43% (May–December 2023), 71% (2024), 88% (2025), and 79% (January–August 2026), while the monthly CF repeatedly fell below the 60% benchmark in the dry season, with a minimum of 33%. The indicative monthly revenue index for 2024 fell by up to 56% from the highest to the lowest month, with a coefficient of variation of 32%, compared with 18% in 2025. Under the level repayment scenario, the monthly DSCR fell below 1.0 for six months in 2024 and three months in 2025, even though the annual DSCR exceeded 1.0; a seasonally sculpted repayment schedule reduced these to four and zero months, respectively.

Third, conceptual implications: these results point to potential seasonal debt stress, a need for liquidity reserves equivalent to at least two months of average revenue, and the relevance of seasonal repayment structures, watershed conservation, and diversification of generation sources for business sustainability. The implications concerning watershed conservation and the management of water abstraction remain propositions, because this study cannot yet establish a causal relationship between watershed conditions or communal water use and discharge decline at the case site. All model results should be read bearing in mind that power and energy are estimated from discharge with a fixed efficiency and an assumption of 24-hour operation without downtime, so actual revenue is likely to be lower than simulated, and that the DSCR is a scenario rather than an actual value. Future research should use actual sold-energy (kWh meter) data and actual loan structures, extend the analysis to other watersheds, directly measure water abstraction volumes within shared watersheds, and empirically test the risk perceptions of lenders and MHP entrepreneurs.

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