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Techno-Economic Feasibility of Pico-Hydropower in Southeast Asia: An Analysis of LCOE and Carbon Emission Reduction

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ABSTRACT

This study evaluates the techno-economic feasibility and carbon reduction potential of pico-hydropower in Southeast Asia, focusing on six representative countries: Indonesia, Malaysia, the Philippines, Vietnam, Laos, and Myanmar. Using a Levelized Cost of Electricity (LCOE) framework, the analysis demonstrates that pico-hydro systems can deliver electricity at costs between 0.04 and 0.11 USD/kWh, significantly lower than diesel-based mini-grids (0.25-0.60 USD/kWh) and comparable to solar PV. Sensitivity analysis indicates that discount rate and capacity factor are the most influential variables affecting LCOE, while capital expenditure plays a moderate role. Environmental assessment shows that a typical 5 kW pico-hydro system operating at a 60% capacity factor can displace 23-27tCO_2 annually if replacing diesel generation. At scale, deployment of 10,000 such systems across Southeast Asia could avoid more than 250,000tCO_2 annually, contributing to member states' Nationally Determined Contributions under the Paris Agreement. Despite these advantages, barriers to widespread adoption include hydrological variability, financing constraints, inadequate policy frameworks, and limited technical capacity at the community level. Opportunities lie in hybridization with solar PV, carbon finance revenues, and integration into rural development strategies. The findings underscore pico-hydro's role as an underutilized but highly promising option for decentralized electrification and climate mitigation in Southeast Asia. Policy support, concessional financing, and capacity-building are essential to unlock its full potential and ensure long-term sustainability. Overall, this study highlights the strategic role of pico-hydro in advancing affordable, low-carbon energy transitions for rural Southeast Asia and offers evidence for its inclusion in regional renewable energy planning.

1. Introduction

1.1 Context and Motivation

Southeast Asia is experiencing one of the fastest rates of energy demand growth globally. The International Energy Agency (IEA) projects that regional electricity demand could triple by 2040 under current policies, with fossil fuels still dominating [1]. This growth, driven by industrialization and urbanization, widens the energy gap between urban and rural areas. Extending centralized grids to remote areas is often uneconomical due to high transmission costs and dispersed populations, making decentralized renewable solutions increasingly attractive [2]. Hydropower accounts for around 35% of the region's renewable generation [3], but large dams such as Nam Theun 2 (Laos) and Bakun (Malaysia) raise social and ecological concerns [4]. In contrast, pico-hydropower, typically below 5 kW, offers a localized, low-impact alternative. By tapping small streams or waterfalls, it can provide reliable off-grid electricity for rural households and communities [5-7].

Pico-hydro is well-suited to Southeast Asia's small river systems, especially in Indonesia, Vietnam, and the Philippines. These sites offer reliable, low-cost energy for lighting, education, small enterprises, and community services. Pico-hydro supports SDG 7 on universal energy access [8]. They also contribute to SDG 13 on climate action by reducing diesel dependence and associated emissions of 0.8-1.0kgCO_2/kWh[9].

Despite significant electrification progress in urban centers, rural and remote populations across Southeast Asia continue to face challenges in accessing reliable electricity. Table 1 presents country-specific electrification rates and estimates of populations without electricity access [1], [10-11].

1.2 Problem Statement

Despite its potential, pico-hydropower remains under-represented in regional energy planning. Most studies merge micro and pico systems, limiting cost and performance data, while Southeast Asian analyses largely focus on solar PV and wind [12-15] creating a lack of comparative understanding for pico-hydro [16-17]. The absence of standardized Levelized Cost of Electricity (LCOE) assessments under local conditions hinders fair comparison with other renewables.

Table 1 Electrification access in Southeast Asia countries.

Country	Electrification Rate (%)	Population without Electricity (millions)
Indonesia	97	8.2
Malaysia	100	0.0
Philippines	95	5.2
Vietnam	99	1.0
Laos	88	1.0
Cambodia	85	2.6
Myanmar	80	11.0
Thailand	100	0.0
Brunei	100	0.0
Singapore	100	0.0

Another critical gap concerns the limited integration of carbon emission reduction analysis. Although hydropower is recognized as a low-emission technology, few studies have quantified pico-hydro's potential to replace diesel-based generation in rural Southeast Asia. This omission is crucial as ASEAN member states have pledged to cut emissions through their Nationally Determined Contributions (NDCs) under the Paris Agreement [18]. For instance, Indonesia targets a 31.89% reduction by 2030, while Vietnam aims for net-zero by 2050 [19]. Without empirical evidence of pico-hydro's carbon savings, technology remains undervalued in climate strategies.

Hydrological variability and climate-change effects, such as altered rainfall, droughts, and flooding, pose additional uncertainty for pico-hydro reliability and financial feasibility [20]. Addressing these research and policy gaps is necessary to guide sustainable, evidence-based rural electrification.

1.3 Objectives

This paper aims to address these research and policy gaps through a comprehensive analysis of pico-hydropower in Southeast Asia. The first objective is to conduct a techno-economic feasibility study of pico-hydro systems by calculating LCOE across representative case studies in Indonesia, Malaysia, the Philippines, Vietnam, Laos, and Myanmar. The second objective is to quantify the potential carbon emission reductions achieved by displacing diesel generators with pico-hydro. The third objective is to perform sensitivity analysis on financial and technical parameters, including discount rate, capital expenditure, and hydrological capacity factor, to assess risks and robustness. The final objective is to provide recommendations for policymakers, financiers, and community stakeholders to enhance the role of pico-hydro in rural electrification and carbon mitigation.

The novelty of this research lies in its comparative regional perspective, offering the first harmonized cross-country assessment of pico-hydropower in six Southeast Asian countries using a consistent LCOE and carbon-emission framework. The analysis shows how hydrology, financing, and policy differences shape techno-economic performance, providing region-specific evidence to guide ASEAN's renewable-energy strategies, financing mechanisms, and community electrification efforts, and positioning pico-hydropower as an important contributor to the region's low-carbon transition.

The paper is organized as follows: Section 2 reviews prior studies on hydropower development and pico-hydro impacts. Section 3 outlines the LCOE, carbon, and sensitivity methods. Section 4 presents techno-economic and carbon-reduction results for Southeast Asia. Section 5 discusses financial and policy implications, and Section 6 concludes with key recommendations and future research directions.

2. Literature Review

2.1 Economic Assessments of Pico-Hydropower

Economic feasibility is a critical factor in renewable energy adoption. The LCOE provides a standardized metric to compare technologies, capturing capital expenditure, operation and maintenance costs, and generation output over a system's lifetime [21]. Globally, pico-hydro has demonstrated highly competitive LCOE values, often ranging between 0.04 and 0.12USD/kWh, depending on site characteristics and financing [5], [22-23]. These values are substantially lower than diesel-based generation, which in rural Southeast Asia typically ranges from 0.25 to 0.60USD/kWh due to fuel and logistics costs [9].

Table 2 compiles key empirical and technical studies on pico-hydropower in Southeast Asia, summarizing system types, capacities, and cost or performance data relevant to LCOE modelling. Although direct pico-scale LCOE values are limited, the literature provides CAPEX benchmarks, O&M ratios, component cost structures, and measured energy costs from community projects. Together, these studies establish a realistic cost basis for 0.1–5 kW systems in the six selected countries and justify the input parameters used in this analysis.

2.2 Environmental and Social Impacts

Beyond its economic feasibility, pico-hydropower delivers key environmental and social co-benefits that reinforce its sustainability. Environmentally, run-of-river designs divert limited streamflow without large reservoirs, avoiding methane emissions typical of big dams [18], [34-35]. Lifecycle emissions are only 10-15gCO_2/kWh which is far lower than conventional hydropower (23-24gCO_2/kWh) or coal (800gCO_2/kWh) [36]. The ecological footprint is therefore minimal, with limited disruption to aquatic ecosystems and surrounding land use when properly designed.

Socially, pico-hydro enhances rural welfare by providing clean, reliable electricity for lighting and study, reducing kerosene use and indoor air pollution [37-38]. In addition, it also powers productive activities such as rice milling, sewing, and agro-processing, boosting local incomes, while healthcare services benefit from lighting and vaccine refrigeration that improve healthcare access and quality [39-40].

2.3 Research Gaps in Southeast Asia

Despite these advantages, research on pico-hydropower in Southeast Asia remains fragmented. Much of the regional scholarship focuses on large hydropower, often in relation to energy security and transboundary water politics [41-42]. Studies that do examine small-scale hydro tend to emphasize micro-hydro systems above 10kW, leaving pico-hydro underrepresented [43].
A major gap concerns the integration of techno-economic analysis with carbon reduction potential. While LCOE studies have been conducted for PV, wind, and bioenergy in the region, very few provide comparative cost data for pico-hydro under localized Southeast Asian conditions [29]. Likewise, emission reduction estimates are rarely included, despite Southeast Asia member states committing to ambitious climate targets in their Nationally Determined Contributions (NDCs) [19]. Another weakness is the limited incorporation of climate change impacts. Hydrological variability due to changing rainfall patterns, droughts, and floods has been identified as a key risk to hydropower reliability [20], yet empirical studies on pico-hydro resilience remain scarce.

Table 2 Summary of relevant prior studies on pico-hydro.

Country	Study/ Source	System Type	System Size	Cost / Performance Data	Usefulness for LCOE Modelling
Malaysia [24-25]	Basar, M.F. et al. (2014). *Cost Analysis of Pico Hydro Turbine for Power Production.*	• Run-of-river, • Turbine-based pico-hydro	0.5-5 kW	CAPEX breakdown	Supports CAPEX structure and component-level modelling for pico systems.
	Musa, M. et al. (2018). *Small Scale Hydro Turbines for Sustainable Rural Electrification.*	• Very small hydro • Run-of-river	4.75 kW	Provides the cost of energy and system cost.	Offers empirical cost-per-kWh data for comparison against LCOE results.
Indonesia [26-27]	Bachtiar, B.N. et al. (2022). *Feasibility Study on the Development of a Pico-hydro Power Plant for Village Electricity Using a Centrifugal Pump as Turbine (PAT) Prime Mover*	• Run-of-river • Pelton-type pico-hydro	1-5 kW	CAPEX: 700-3000 USD/kW	LCOE calculation (CAPEX + output).
	Motwani, K.H. et al. (2013). *Cost Analysis of Pump as Turbine for Pico-Hydropower Plants – A Case Study.*	Pump-as-turbine (PAT) pico-hydro	3 kW	CAPEX, O&M, PAT vs turbine cost comparison.	Supports low-CAPEX scenario in sensitivity analysis.
Philippines [28]	ADB Technical Assistance Consultant's Report (2015). *Republic of the Philippines: Rural Community-Based Renewable Energy Development in Mindanao.*	• Community pico-hydro • Run-of-river	0.3-3 kW	Delivered electricity at 0.08-0.12 USD/kWh (measured).	Provides a real-world LCOE benchmark for Southeast Asia.
Vietnam [29]	Nguyen, P.A., Abbott, M., & Nguyen, T.L.T. (2019). *The development and cost of renewable energy resources in Vietnam*.	• Small/ Pico hydro • Run-of-river	0.3-10 kW	Provides CAPEX ranges; O&M typically 2-5% of CAPEX	CAPEX/O&M
Laos [30]	Smits, M. & Bush, S.R. (2010). *A light left in the dark: The Practice and Politics of Pico-Hydropower in the Lao PDR.*	• Community pico-hydro • Run-of-river	0.1-1 kW	Unit cost: USD 50-120 per turbine; >60,000 units installed.	Supports CAPEX variability and rural market pricing behaviour.
Myanmar [31]	Thema, J. Gericke, N. et al. (2020) *Community-based energy projects in Myanmar: Study on rural renewable energy projects and the potential contribution of cooperatives to a sustainable electrification*	• Small/ pico-hydro • Off-grid	<5 kW	Reports CAPEX and energy output for rural hydro sites.	Provides country-level CAPEX boundaries.
Regional / Global [32-33]	IRENA (2023). *Renewable Power Generation Costs in 2023.*	• Small/ pico-hydro	1-10 kW	LCOE: 0.05-0.10 USD/kWh in developing Asia	Global benchmark for validating regional LCOE values.
	Klein, S.J.W. (2022). *A Review of Small Hydropower Performance and Cost.*	• Small/ pico-hydro	1-10 kW (classified under small hydro)	Global LCOE: 0.02-0.11 USD/kWh.	Provides internationally accepted LCOE boundaries.

Finally, institutional and financial barriers receive insufficient attention. While community ownership models have succeeded in parts of South Asia, questions remain about financing, operation, and maintenance under Southeast Asian governance structures. Addressing these gaps is essential to evaluate pico-hydro's true potential as a cost-effective and sustainable electrification strategy for rural communities.

3. Methodology

3.1 Scope and Case Selection

The methodology for this study was designed to assess the techno-economic feasibility of pico-hydropower across representative Southeast Asian contexts. Six countries were selected because of their abundant hydro resources and significant rural electrification challenges. These countries account for the majority of the region's unelectrified population and have diverse hydrological and socioeconomic conditions [44]. Representative case studies were developed using data from small rivers and streams in rural or mountainous regions, where pico-hydro is most applicable. Streamflow and elevation drop data were sourced from national hydrological surveys and regional datasets [45]. Socioeconomic inputs, including household energy demand and willingness to pay, were obtained from Southeast Asia energy outlooks and field studies [10], [38]. The system boundary for the analysis is defined at the community scale, with typical pico-hydro installations ranging from 500 W to 5 kW. The study assumes run-of-river designs without reservoirs, in line with common practices in Southeast Asia [34].

The study employed an analytical test system integrating the LCOE and carbon emission reduction models. Each selected country served as a representative test system reflecting local hydrological and economic conditions. Input parameters such as installed capacity (0.5-5kW), capital expenditure (CAPEX), Operation and Maintenance (O&M) cost, and capacity factors were analyzed using secondary data. The approach was computational rather than experimental, ensuring comparability across all regional cases.

3.2 Levelized Cost of Electricity (LCOE) Framework

The LCOE was adopted as the principal economic metric in this study to evaluate the feasibility of pico-hydropower relative to diesel and solar PV systems. LCOE is widely regarded as a standardized indicator that measures the average cost of electricity over the lifetime of a power plant, expressed in USD/kWh. It enables comparison across technologies with different investment profiles, lifetimes, and operating characteristics, which is useful for decentralized renewable systems such as pico-hydro [21], [46]. It can be calculated as:

$$LCOE = \frac{\sum_{t=0}^{n} \frac{I_t + O_t + F_t}{(1+r)^t}}{\sum_{t=0}^{n} \frac{E_t}{(1+r)^t}} \quad (1)$$

where:

- I_t = investment cost in year t (USD)
- O_t = operation and maintenance cost in a year t (USD)
- F_t = fuel cost in year t (USD; assumed negligible for hydro)
- E_t = electricity generated in the year t (kWh)
- r = discount rate (%)
- n = project lifetime (years)

The numerator represents the present value of total system costs, including capital, installation, and recurring expenses, while the denominator is the discounted total energy output. For pico-hydro, I_t covers turbine, generator, civil works, and installation, and O_t remains low due to the simplicity and low maintenance of run-of-river designs. The LCOE framework thus effectively evaluates long-term economic feasibility and enables consistent comparison across renewable technologies [15], [22].

The overall analytical process of deriving LCOE for pico-hydro is summarized in Figure 1, which illustrates the flow from input parameters through cost and generation calculations to the final LCOE output. The framework shows the stepwise process of translating input parameters into present value costs and generation, which are combined to yield the LCOE (USD/kWh) [21-22], [46].

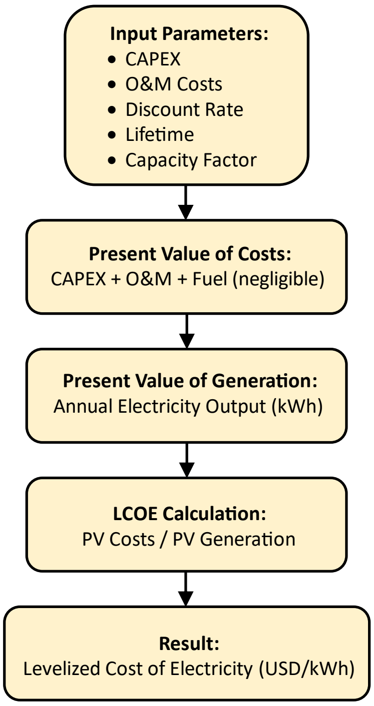

Fig. 1 LCOE framework for pico-hydro analysis.

One key strength of the LCOE framework is its ability to integrate site-specific conditions. For pico-hydro, the capacity factor is strongly influenced by hydrological characteristics. Perennial streams, such as those in Lao PDR, allow for higher capacity factors and thus lower LCOE, while monsoonal rivers in Myanmar or the Philippines result in more variable generation profiles and higher costs per kWh [31,33]. Financing costs also play a critical role, as the discount rate significantly alters the present value of both costs and generation. As shown later in the sensitivity analysis, the difference between concessional financing at 5% and commercial borrowing at 12% can raise LCOE by more than 40% [30], [32].

For comparative purposes, the same LCOE framework was uniformly applied to solar PV and diesel mini-grids to ensure methodological consistency across technologies. This framework not only provides a rigorous basis for evaluating pico-hydro systems but also offers a transparent metric that enables policymakers and financiers to compare technologies on an equal footing. When integrated with the carbon-emission analysis in Section 3.3, it captures both the economic and environmental dimensions of sustainability, serving as a comprehensive decision-making tool for rural electrification strategies in Southeast Asia.

3.3 Carbon Emission Reduction Analysis

The carbon reduction potential of pico-hydropower was estimated by comparing its output with diesel mini-grids, which remain the main power source in many remote Southeast Asian areas [9,33]. As a run-of-river system, pico-hydropower emits negligible operational CO_2 since it avoids methane generation from large reservoirs [18], [34]. Its lifecycle emissions, mainly associated with construction materials and equipment, are approximately 10-15gCO_2/kWh, about 50 to 80 times lower than diesel (≈900gCO_2/kWh) and comparable to solar PV (≈40gCO_2/kWh) [35], [36], [37]. The annual carbon savings are calculated as:

$$CO_{2,saved} = E_{gen} \times EF_{baseline} - E_{gen} \times EF_{pico} \quad (2)$$

where E_{gen} is the annual electricity generation (kWh/year), $EF_{baseline}$ is the emission factor of diesel generation (kgCO_2/kWh) and EF_{pico} is the lifecycle emission factor of pico-hydro (kgCO_2/kWh). For practical purposes, EF_{pico} is generally negligible and can be approximately zero in rural deployment analyses [37], [47].

For illustration, a 5kW pico-hydro system operating at a 60% capacity factor generates approximately 26,300 kWh/year. Assuming a diesel baseline of 0.9kgCO_2/kWh, this equates to annual avoided emissions of roughly 23.7tCO_2. Even after accounting for lifecycle emissions of 0.01kgCO_2/kWh from pico-hydro, the net savings remain 23.4tCO_2 per system per year.

Scaling these results regionally demonstrates significant mitigation potential. If 10,000 such systems were installed across Southeast Asia, the annual displacement would exceed 234,000tCO_2, equivalent to removing nearly 50,000 passenger cars from the road [36], [44]. For countries with high rural electrification deficits, such as Indonesia and Myanmar, pico-hydro deployment at scale could contribute directly to achieving sectoral decarbonization targets under their Nationally Determined Contributions (NDCs). Furthermore, the potential to register such projects under voluntary carbon markets could provide an additional revenue stream, making community-led pico-hydro financially more attractive [33].

The analysis also reveals an important co-benefit: avoided emissions of local air pollutants. Diesel mini-grids are not only carbon-intensive but also emit significant quantities of particulate matter, nitrogen oxides (NO_x), and sulfur dioxide (SO_2), all of which contribute to poor indoor and outdoor air quality. Substituting diesel with pico-hydro eliminates these pollutants, generating positive health outcomes for rural households [38-39].

In summary, the carbon reduction analysis positions pico-hydro as a dual-benefit technology, contributing both to climate mitigation and to public health improvements. Its low lifecycle emissions, when compared to diesel and even grid-based fossil power, provide a strong justification for integrating pico-hydro into climate finance frameworks and sustainable rural energy strategies.

3.4 Input Parameters and Assumptions

The reliability of techno-economic analysis depends on transparent, high-quality assumptions. This study draws input parameters from regional cases, global benchmarks, and institutional datasets to reflect realistic Southeast Asian conditions, covering technical, financial, and environmental factors that shape LCOE and emission results. To enhance transparency and reproducibility, an Excel-based LCOE calculator is provided as Supplementary Material (Supplementary File S1).

On the technical side, system capacities of 0.5 to 5kW represent typical rural pico-hydro scales [5], [38]. Capacity factor assumptions ranged from 40% to 80%, capturing the hydrological diversity of Southeast Asia. The lower limit (40%) represents monsoonal regimes in the Philippines and parts of Myanmar with long dry seasons, while the upper limit (80%) reflects perennial high-flow rivers in northern Laos and Vietnam that allow near-continuous generation [45], [48]. A project lifetime of 20 to 25 years was selected, consistent with global pico-hydro experience, requiring minimal maintenance [22], [49].

Financial assumptions included capital expenditure (CAPEX) between 2,500 and 4,000 USD/kW, reflecting variations in equipment sourcing, transportation costs to remote areas, and differences in local fabrication capabilities [38-39]. Annual operation and maintenance (O&M) costs were set at 2% to 5% of CAPEX, consistent with rural mini-grid benchmarks [23], [50]. Discount rates were modeled between 5% and 12%, capturing the contrast between concessional finance available through international development banks and higher commercial borrowing rates in less stable financial contexts [44], [46]. The lower bound (≈5%) represents concessional financing conditions commonly offered by multilateral development agencies such as the World Bank or Asian Development Bank (ADB), whereas the upper bound (≈12%) corresponds to commercial or private-sector financing that reflects higher perceived investment risks and limited credit access in rural Southeast Asia.

Table 3 Parameters for LCOE and Carbon Analysis.

Parameter	Value/ Range	Remarks
Installed capacity	0.5-5kW	Typical pico-hydro range for rural use [5], [38].
CAPEX	2,500-4,000USD/kW	Includes turbine, generator, civil works, and logistics costs [22], [39], [49].
O&M costs	2-5% of CAPEX annually	Based on IRENA and community project data [22], [50].
Lifetime	20-25 years	Standard system lifespan [46].
Discount rate	5-12%	Range for concessional to commercial loans [19], [29].
Capacity factor	40-80%	Reflects regional hydrological variation [51-52].
Diesel emission factor	0.8-1.0kgCO_2/kWh	Based on IPCC and regional diesel studies [36], [47].

Finally, environmental parameters were included to estimate avoided emissions. A diesel baseline of 0.8-1.0kgCO_2/kWh was applied, in line with IPCC guidelines and empirical Southeast Asia studies [36], [47]. Pico-hydro lifecycle emissions were assumed to be approximately 10-15gCO_2/kWh, negligible compared to diesel or even solar PV [37].

While operational emissions are minimal, this estimate does not fully capture embodied carbon from materials such as steel and concrete, or emissions from transportation to remote and island sites. Reported values in the literature range from 8 to 2gCO_2/kWh depending on system scale, material composition, and logistics distance. Therefore, the 10-15gCO_2/kWh value applied in this study represents a conservative central estimate for regional comparability, acknowledging potential variations under different site conditions. These assumptions, summarized in Table 3, provide the foundation for the LCOE and carbon reduction modeling conducted in subsequent sections.

The parameters in Table 3 were derived from regional reports, institutional databases, and previous pico-hydro studies to represent realistic community-scale systems in Southeast Asia. Installed capacity values reflect typical rural applications, while CAPEX and O&M ranges capture the average costs of construction and maintenance. Routine maintenance and minor repairs are included, whereas infrequent major expenses, such as turbine replacement, channel rehabilitation, and remote logistics, were excluded due to limited project data but are acknowledged as potential contributors to long-term cost variability. To enhance data transparency and reproducibility, the provenance of the key input parameters is summarized in Table 4.

Table 4 Data Provenance for Key Input Parameters Used in LCOE and Carbon Analysis.

Parameter	Country / Region	Year	Data Type	Sample Size
CAPEX (USD/kW)	Malaysia, Indonesia, Philippines, Vietnam, Laos, Myanmar	2020–2024	Literature synthesis (expert-estimated average)	6 regional case studies
O&M (% of CAPEX)	Regional (Southeast Asia)	2019–2024	Benchmark synthesis (derived estimate)	5 community-scale references
Capacity Factor (%)	• Laos: 70% - 80% • Vietnam: 60% - 75% • Malaysia: 55% - 65% • Indonesia: 50% - 70% • Myanmar: 45% - 65% • Philippines: 40% - 50%	2018–2024	Mixed (field-measured and modeled)	6 hydrology-based case studies
Diesel Emission Factor (kgCO_2/kWh)	ASEAN average (Southeast Asia mini-grids)	2011–2023	IPCC and empirical datasets	5 regional and international sources
Pico-hydro Lifecycle Emission (gCO_2/kWh)	Global benchmark applied to Southeast Asia	2019–2022	Literature-based lifecycle estimate	2 international studies (IPCC & peer-reviewed)

Table 5. Sensitivity scenarios and assumptions for LCOE modelling [38-39], [44-47].

Parameter	Base Case	Low Case	High Case	Rationale
Discount Rate	8%	5% (concessional finance)	12% (commercial loan)	Reflects financing conditions from concessional to commercial borrowing.
CAPEX	3,000USD/kW	−20% (2,400USD/kW)	+20% (3,600 USD/kW)	Accounts for equipment, logistics, and exchange rate variability.
Capacity Factor	60%	40% (seasonal variability)	80% (perennial streams)	Represents hydrological diversity across Southeast Asia.

Furthermore, discount rates of 5-12% were adopted to capture variations in national financing conditions. This simplified approach represents the cost of capital at a regional level but does not explicitly model debt/equity ratios, grant support, or cash-flow timing for subsidies. In practice, many community-based pico-hydro projects rely on blended financing, including partial grants or in-kind contributions from NGOs and local authorities, which can lower effective LCOE. The model, therefore, reflects a uniform financing assumption to maintain comparability across countries. Meanwhile, capacity factors of 40-80% represent seasonal hydrological fluctuations observed in typical pico-hydro operations.

In this study, capacity factors were modeled as fixed scenarios (40-80%) to represent typical low, medium, and high hydrological conditions across Southeast Asia. Although this deterministic approach simplifies the analysis, it does not capture seasonal or multi-year hydrological variability. Future work should integrate stochastic or time-series hydrological modeling to account for seasonal flow fluctuations, drought events, and long-term climate impacts on pico-hydro reliability.

The lifetime (20-25 years) and diesel emission factor (0.8-1.0kgCO_2/kWh) were selected according to regional energy and environmental guidelines. These assumptions provide a balanced representation of techno-economic and environmental conditions across ASEAN member states.

3.5 Sensitivity Analysis

Sensitivity analysis was incorporated to evaluate the robustness of the Levelized Cost of Electricity (LCOE) estimates under uncertain real-world conditions. This is particularly important for pico-hydropower projects in Southeast Asia, where site-specific hydrological variability, financial constraints, and logistical challenges can significantly influence project outcomes [50]. By systematically varying key parameters, the analysis identifies which factors exert the strongest influence on economic viability, thereby providing insights into policymakers, developers, and financiers.

Three primary parameters were tested: discount rate, capital expenditure (CAPEX), and capacity factor. The discount rate captures the cost of financing and risk perceptions in different national contexts. Given that concessional loans are often available through multilateral development banks, a lower bound of 5% was modeled to reflect favorable financing scenarios, while an upper bound of 12% represented commercial borrowing in less stable financial environments [44], [46]. CAPEX was varied by ±20% to account for fluctuations in equipment costs, transportation challenges in remote areas, and exchange rate risks, all of which are highly relevant in archipelagic nations such as Indonesia and the Philippines [38], [39].

The capacity factor was modeled between 40% and 80%, reflecting hydrological diversity across Southeast Asia. Sites with perennial streams, such as those in Laos and Vietnam, can sustain capacity factors closer to 70-80%, while locations subject to strong dry-season variability, particularly in Myanmar and the Philippines, may operate closer to the lower bound [45], [47]. The sensitivity scenarios are summarized in Table 5, which presents the base, low, and high cases applied in the modeling framework.

The results of the sensitivity analysis were visualized through spider plots, which enabled clear identification of the most critical drivers. Preliminary outcomes indicate that discount rate and capacity factors are the most influential parameters, with CAPEX playing a secondary but still important role. These findings emphasize the importance of policy interventions that reduce financing costs and improve hydrological mapping, while technical training and local manufacturing could help mitigate CAPEX variability in the long term.

3.6 Analytical Framework

The analytical framework integrates technical, economic, and environmental aspects to holistically assess pico-hydropower feasibility in Southeast Asia. It follows a logical sequence from data collection to energy estimation, LCOE modeling, and carbon reduction analysis with sensitivity testing, ensuring results are both technically sound and policy relevant.

At the core of the framework, the LCOE model captures long-term generation costs, including capital, O&M, and financing factors [21]. A complementary module estimates avoided emissions relative to diesel mini-grids, common in rural Southeast Asia [9], [47]. By combining these two dimensions, they assess both economic viability and climate benefits in an integrated analysis.

A key feature of the framework is the incorporation of sensitivity analysis, as described in Section 3.5. By varying critical parameters such as discount rate, CAPEX, and capacity factor, the analysis tests the robustness of LCOE results under different real-world conditions [38], [44]. This provides policymakers with a clearer understanding of which factors are most influential and where interventions can yield the greatest impact.

The overall analytical process is summarized in Figure 2**,** which illustrates the flow from input data to final outputs. This visualization underscores the interconnections between hydrological resources, economic modeling, and environmental impacts. Such a framework is adaptable and can be applied to other decentralized energy systems, ensuring its broader relevance beyond pico-hydro.

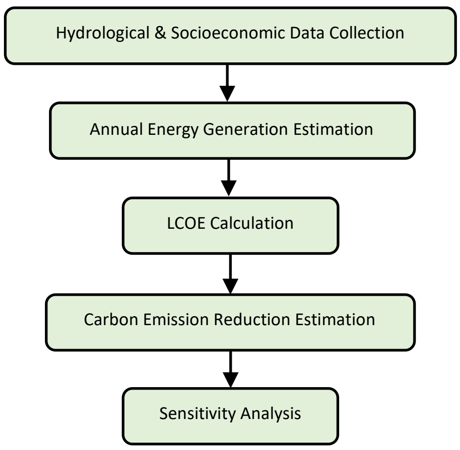

Fig. 2 Methodological framework for techno-economic and carbon emission reduction analysis of pico-hydro systems.

4. Results and Analysis

4.1 Techno-Economic Feasibility

The LCOE results for pico-hydropower systems across Southeast Asia countries demonstrate clear competitiveness when compared to diesel-based generation and, in many cases, solar PV. The modeled results indicate that pico-hydro can deliver electricity at costs ranging from 0.04 to 0.11USD/kWh, depending on local hydrological and financial conditions.

Laos and Vietnam showed the lowest costs, between 0.04 and 0.07USD/kWh, reflecting their strong hydrological resources, high-capacity factors, and the presence of domestic manufacturing capabilities for turbines and related equipment. Malaysia also reported favorable outcomes, with LCOE values averaging 0.05-0.08USD/kWh, aided by robust infrastructure and relatively low financing costs.

Indonesia's results varied significantly across provinces. Highland areas of Sulawesi and Papua offered LCOE values as low as 0.06USD/kWh, while flatter regions with limited water flow produced results closer to 0.10USD/kWh. This variability highlights the importance of site selection and the need for reliable hydrological data [30-31]. The Philippines recorded the highest average LCOE (0.08-0.11USD/kWh), largely due to logistical costs in transporting equipment across multiple islands and challenges in sustaining high-capacity factors during the dry season. Specifically, the LCOE increased from approximately 0.05 USD/kWh in Laos to 0.11USD/kWh in the Philippines, representing a 55-60% cost difference between the most and least favorable cases. This variation reflects the combined effects of hydrological inconsistency, transportation cost escalation, and limited access to concessional financing in island economies.

Table 6 presents a comparative assessment of the LCOE for pico-hydro, diesel, and solar PV across selected Southeast Asia countries, providing insights into their relative cost competitiveness for rural electrification.

The results consistently confirm that pico-hydro is cheaper than diesel across all studied contexts, with margins of 60-80%. Compared with solar PV, pico-hydro offers competitive or lower costs in areas with strong hydrology, though in low-flow regions, solar PV may become more attractive due to higher hydro variability. Importantly, pico-hydro provides baseload electricity, eliminating the need for costly storage solutions that inflate the effective LCOE of PV-battery systems [52].

Table 6 LCOE comparison of pico-hydro with diesel and solar PV across selected Southeast Asia countries.

Country	Pico-Hydro LCOE (USD/kWh)	Diesel (USD/kWh)	Solar PV Off-Grid (USD/kWh)
Indonesia	0.06-0.10	0.28-0.55	0.10-0.18
Malaysia	0.05-0.08	0.25-0.45	0.09-0.15
Philippines	0.08-0.11	0.30-0.60	0.12-0.20
Vietnam	0.05-0.07	0.26-0.40	0.08-0.14
Laos	0.04-0.07	0.25-0.42	0.08-0.13
Myanmar	0.06-0.09	0.32-0.58	0.11-0.18

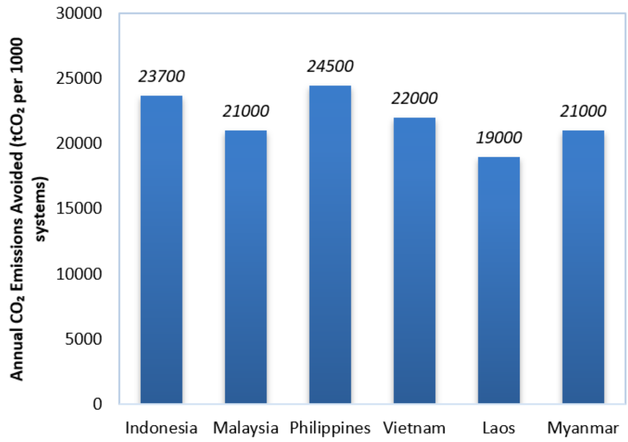

Fig. 3 Annual CO_2 emissions avoided by a typical 5kW pico-hydro system replacing diesel generation in Southeast Asia.

4.2 Carbon Emission Reduction

Replacing diesel-based generation with pico-hydro results in substantial reductions in carbon dioxide emissions. For a typical 5kW system operating at a 60% capacity factor (CF), annual generation is approximately 26,300kWh. With a diesel emission factor (EF) of 0.9kgCO_2/kWh, this equates to annual avoided emissions of 23.7 metric tons of CO_2. The results presented in Figure 3 are derived from the authors' calculations using data from [36], [44], and [47], assuming a 5kW pico-hydro system operating at a 60% capacity factor and scaled to 1,000 installations per country.

Under these conditions, pico-hydro achieves annual carbon offsets ranging from 19,000tCO_2 in Laos to 24,500tCO_2 in the Philippines, thereby contributing directly to the achievement of Southeast Asia member states' NDC commitments. These variations reflect differences in system load factors and diesel displacement rates. Figure 3 has been redrawn with labeled units (tCO_2/year for 1,000 installations) for clarity and improved visual comparison across countries.

At the country level, if 1,000 systems were deployed in underserved communities, the cumulative reductions would be 23,700tCO_2 in Indonesia, 24,500tCO_2 in the Philippines, and 21,000tCO_2 in Myanmar annually. At the regional level, deployment of 10,000 units could avoid over 250,000tCO_2 annually, a significant contribution toward Southeast Asia's collective NDC targets [19], [44]. These results highlight not only the direct mitigation benefits of pico-hydro but also its alignment with climate finance mechanisms. Projects with verified emission reductions may qualify for voluntary carbon markets, potentially generating additional revenue streams for communities [47].

Table 7 presents a sensitivity analysis of the lifecycle emission factor (EF) for pico-hydro systems and its impact on avoided CO_2 emissions and potential carbon revenue. The EF values (10-40gCO_2/kWh) represent the possible range of lifecycle emissions depending on materials, transport, and installation conditions. A lower EF means a cleaner system that avoids more carbon.

For a 5kW pico-hydro system operating at a CF of 60% (26,300 kWh/year), the avoided emissions range from 22.6 to 23.4tCO_2 annually. This translates to potential carbon revenues of USD 226–234 per system or up to USD 2.3 million for 1000 systems at high carbon prices. These results confirm that pico-hydro offers tangible carbon savings that can generate additional income through carbon markets while advancing rural electrification goals.

Table 7 Lifecycle emissions sensitivity and carbon revenue (5kW, CF = 60%, 26,300kWh/year; diesel EF = 0.9kgCO_2/kWh).

Pico-Hydro EF (g CO_2/kWh)	CO_2 Avoided per Year (tCO_2)	Carbon Revenue at USD 10 per tCO_2 (USD/yr)	Carbon Revenue at USD 50 per tCO_2 (USD/yr)	Carbon Revenue at USD 100 per tCO_2 (USD/yr)	CO_2 Avoided for 1000 Systems (tCO_2/yr)	Total Revenue at USD 10/t (USD/yr)	Total Revenue at USD 50/t (USD/yr)	Total Revenue at USD 100/t (USD/yr)
10	23.41	234	1170	2341	23407	234070	1,170350	2,340700
20	23.14	231	1157	2314	23144	231440	1,157200	2,314400
30	22.88	229	1144	2288	22881	228810	1,144050	2,288100
40	22.62	226	1131	2262	22618	226180	1,130900	2,261800

4.3 Sensitivity Analysis

Sensitivity analysis was conducted to identify the key parameters influencing the LCOE for pico-hydropower systems in Southeast Asia. As summarized in Table 4, the discount rate was varied between 5% (concessional finance) and 12% (commercial borrowing), CAPEX was adjusted by ±20% to represent logistical and cost uncertainties, and the capacity factor ranged from 40% to 80% to capture hydrological diversity across the region [38-39], [44], [47].

The analysis revealed that the discount rate and capacity factor exert the strongest influence on LCOE outcomes. Increasing the discount rate from 5% to 12% raised the average LCOE from 0.05 to 0.09USD/kWh (an increase of approximately 40%), while reducing the capacity factor from 70% to 40% nearly doubled the LCOE from 0.06 to 0.12USD/kWh. These relationships are illustrated in the revised Figure 4, which highlights the sensitivity of pico-hydro economics to financial and operational parameters.

CAPEX variation produced a more moderate effect, where ±20% changes shifted LCOE by 12-18%. These relationships, illustrated in Figure 4, indicate that financing conditions and hydrological performance dominate the economic viability of pico-hydropower, while equipment and installation costs play a secondary yet meaningful role.

A detailed parametric sensitivity analysis further confirmed that LCOE is most responsive to the capacity factor, followed by the discount rate and CAPEX. Increasing the capacity factor from 30% to 60 % reduced LCOE by approximately 35%, whereas a 10% rise in CAPEX increased LCOE by about 8%. These results underscore the importance of improving turbine efficiency, ensuring consistent streamflow, and maintaining affordable financing conditions to achieve sustainable system economics.

Capacity factor remains particularly critical, as lower streamflow distributes fixed capital costs over fewer kilowatt-hours of generation. This effect is amplified in monsoonal regions, where seasonal flow fluctuations can markedly impact performance.

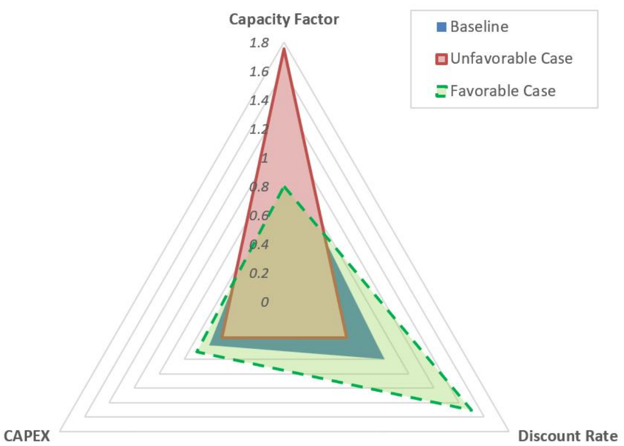

Fig. 4 Sensitivity of pico-hydro LCOE to key parameters.

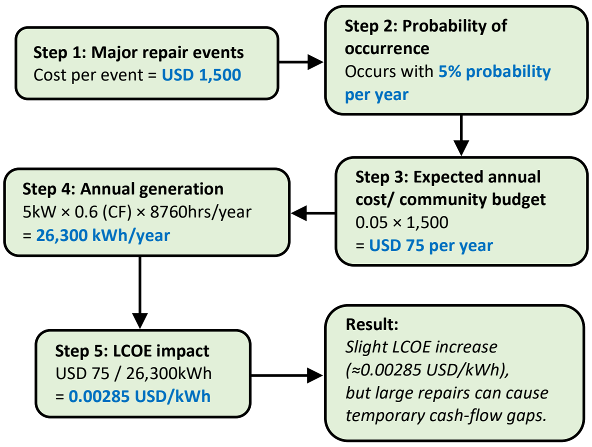

Fig. 5 Illustration of shock scenario.

Although less dominant than hydrology or financing, capital costs remain relevant in remote and island locations where transport and installation are expensive [39], [49].

To illustrate the potential financial impact of unexpected maintenance events, Figure 5 presents an O&M shock scenario in which a 5% annual probability of a major repair costing USD 1,500 results in an expected annual cost of USD 75. This additional cost slightly increases the LCOE by approximately 0.00285 USD/kWh, emphasizing the importance of preventive maintenance and budgeting in community-based pico-hydro systems.

In addition to these parametric tests, the financial model was refined to evaluate how different financing structures influence project economics. Three representative mixes were analyzed: (i) 100% concessional loan at 5%, (ii) 50% grant + 50% community loan at 6%, and (iii) full commercial borrowing at 12%. The resulting LCOE and payback periods are summarized in Table 8, illustrating how concessional and blended financing substantially reduce project costs and improve investment recovery.

Table 8 Summary of LCOE and Payback Periods Under Different Financing Mixes.

Financing Mix	Discount Rate (%)	LCOE (USD/kWh)	Payback @ USD 0.15/kWh	Payback @ USD 0.30/kWh
100% Concessional Loan (5%)	5	0.063	10 years	3 years
50% Grant + 50% Community Loan (6%)	3	0.036	4 years	2 years
Full Commercial Borrowing (12%)	12	0.094	12 years	4 years

**Calculations assume CAPEX = USD 15,000, O&M = 3% per year, lifetime = 20 years, CF = 60%.*

The results clearly show that financial structure strongly influences project feasibility. Under concessional or blended financing, LCOE drops by up to 60% (from 0.094 to 0.036 USD kWh^{-1}), while payback periods shorten from 12 to 4 years at community tariff levels. This improvement highlights the importance of low-cost credit and grant blending in enhancing the affordability and investment attractiveness of pico-hydro for rural electrification.

The implications are significant for policymakers and financiers. In countries such as Myanmar and the Philippines, where financing costs are relatively high and river flows are seasonal, pico-hydro projects face elevated risks without targeted interventions. Conversely, in Laos and Vietnam, favorable hydrological conditions and access to concessional lending reduce sensitivity and strengthen feasibility. Thus, ensuring affordable financing and improving hydrological mapping emerge as priority strategies for scaling pico-hydro in Southeast Asia.

4.4 Comparative Analysis with Alternative Technologies

To contextualize the techno-economic performance, pico-hydropower was compared with solar PV and diesel mini-grids, the main rural electrification options in Southeast Asia. Diesel's LCOE (0.25–0.60 USD/kWh) remains far above pico-hydro. Its LCOE ranges from 0.25-0.60USD/kWh, especially high in remote islands [47], [49]. In comparison, pico-hydro achieves 0.04-0.11USD/kWh at favorable sites, highlighting its low-cost, low-carbon advantage.

Solar PV mini grids, another growing alternative, show LCOE values ranging from 0.07 to 0.18USD/kWh depending on capacity, storage integration, and financing terms [21], [52]. While PV has advantages in modularity and rapid deployment, its intermittency and reliance on battery storage increase both costs and system complexity. Pico-hydro, in contrast, offers continuous generation in suitable sites, reducing the need for storage and enhancing system reliability [38].

From an environmental perspective, pico-hydro further outperforms diesel by avoiding 23-27tCO_2 annually per 5kW system. For comparison, diesel-based generation emits approximately 0.9kgCO_2/kWh, while solar PV emits around 40gCO_2/kWh, nearly three times higher than pico-hydro's 15gCO_2/kWh [36-37]. Taken together, these comparisons suggest that pico-hydro is not only cost-competitive but also environmentally superior, particularly in rural areas with sufficient hydrological resources. Thus, it represents a complementary solution alongside solar PV, with hybrid systems offering the most resilient electrification pathway for community electrification in Southeast Asia communities [44], [50].

4.5 Regional Implications

The comparative results show that while pico-hydro is economically competitive, its expansion in Southeast Asia depends on strong policy and financing support. Sensitivity analysis identified the discount rate as a key factor: with concessional financing at 5%, LCOE dropped to 0.04 USD/kWh, but at 12% rose over 40% [44], [46]. Affordable financing through subsidies, soft loans, or guarantees is therefore crucial for large-scale adoption.

Current policies in many Southeast Asian countries favor large renewables or solar PV, leaving pico-hydro overlooked [28]. Integrating it into rural energy plan, especially in Indonesia, Vietnam, and Myanmar would diversify and strengthen electrification. Simplified licensing and permitting for small-scale hydro could further reduce delays and costs [46].

The main barriers and potential financing solutions are summarized in Table 9, which links challenges such as high financing costs, CAPEX risks, and limited revenue streams to specific policy and financial interventions. Concessional loans, carbon market access, and blended finance can address these challenges and improve project viability [36], [38-39], [44-47]. Overall, aligning policies with targeted financing is essential to realize pico-hydro's scalable rural electrification potential in Southeast Asia.

Table 9 Policy and financing barriers with recommended solutions [36], [38-39], [44-46].

Barrier	Implication	Policy/Financing Solution
High financing costs (commercial borrowing rates up to 12%)	Raises LCOE by 30-45%, reducing competitiveness	Concessional loans, interest subsidies, and credit guarantees
Limited policy recognition of pico-hydro in national plans	Restricts the integration of pico-hydro into rural electrification programs	Explicit inclusion in rural energy strategies and NDC targets
Complex licensing and permitting procedures	Delays project approval, increases transaction costs	Simplified regulatory frameworks for projects <5 MW
High upfront CAPEX in remote or island locations	Discourages investment and raises the payback period	Grants, blended finance, and local manufacturing support
Limited revenue streams beyond electricity sales	Reduces financial sustainability for community-managed systems	Access to carbon markets and community-level feed-in tariffs

Table 10 Comparative SOUTHEAST ASIA pico-hydro case studies: performance, barriers, and success factors [38-39], [44], [50], [53].

Country	Capacity Factor	LCOE Range (USD/kWh)	Key Barriers	Success Factors
Indonesia [38]	50-70% (mountain rivers)	0.05-0.08	Logistical challenges, limited policy support	Strong NGO and community involvement
Philippines [39]	40-50% (seasonal variability)	0.10-0.12	Hydrological variability, fragmented policy	Hybridization with solar PV
Lao PDR [45]	70-80% (perennial streams)	0.04-0.06	Limited external financing, rural remoteness	Perennial hydrology, community ownership
Vietnam [44]	60-75% (northern highlands)	0.06-0.07	Policy shifts toward grid expansion	Household adoption in highlands
Myanmar [50]	45-65% (local micro-rivers)	0.08-0.10	Lack of finance, no standards, political risks	Low-cost local construction
Malaysia [54]	55-65% (Sabah & Sarawak)	0.06-0.09	Policy bias toward solar PV	NGO-led training and maintenance

4.6 Regional Case Studies

To illustrate the techno-economic potential of pico-hydropower in Southeast Asia, six representative countries were examined: Indonesia, the Philippines, Lao PDR, Vietnam, Myanmar, and Malaysia. These cases highlight how diverse hydrological conditions, policy frameworks, and rural electrification needs shape project outcomes.

A summary of the six country case studies, including performance indicators, barriers, and success factors, is presented in Table 10. The table highlights that while pico-hydro is regionally viable, outcomes are highly context-specific, shaped by hydrological resources, financing models, and governance arrangements.

5. Discussion

5.1 Policy Implications

The findings confirm that pico-hydropower is a cost-competitive and environmentally sustainable option for rural electrification in Southeast Asia. With LCOE values consistently lower than diesel and comparable to solar PV, pico-hydro presents a viable pathway for expanding energy access in underserved communities. However, its potential has yet to be fully recognized in national energy strategies. Current renewable energy policies in Southeast Asia prioritize large hydropower, solar, and biomass, while pico-hydro remains marginalized [19].

Integrating pico-hydro into national electrification programs could accelerate progress toward Sustainable Development Goal 7 (Affordable and Clean Energy). For instance, Indonesia's *Rencana Umum Energi Nasional* (RUEN) emphasizes renewable deployment but gives limited attention to pico-hydro. A dedicated policy framework could provide incentives for local manufacturing, community training, and concessional finance. Similarly, the Philippines' Household Electrification Development Plan targets 100% electrification by 2030 but largely overlooks pico-hydro as a strategic option, despite its proven effectiveness in pilot projects [39].

Regional collaboration under the Southeast Asia Power Grid framework could also extend to small-scale renewables, promoting knowledge-sharing, joint research, and financing mechanisms tailored to pico-hydro. By recognizing the role of pico-hydro in NDC roadmaps, Southeast Asia member states could leverage international climate finance to scale deployment [44].

5.2 Barriers to Adoption

Despite its favorable economics and environmental advantages, pico-hydropower faces several interrelated technical, financial, institutional, and socio-cultural barriers that constrain its broader deployment in Southeast Asia. Technically, hydrological variability linked to seasonal monsoons and climate change introduces risks to generation reliability. While perennial streams in countries such as Laos and Vietnam provide stable flow conditions, regions like the Philippines often experience dry-season water scarcity, lowering capacity factors and elevating the effective LCOE [50]. Sedimentation and debris during heavy rainfall can also reduce turbine efficiency and increase maintenance needs.

Financially, access to affordable capital remains a critical constraint. As highlighted in the sensitivity analysis (Section 4.3), the discount rate strongly influences LCOE outcomes. In markets with limited concessional finance, such as Myanmar, high commercial lending rates can erode cost competitiveness. Continued donor support and soft-loan programs from multilateral development banks are therefore vital to sustain rural deployment [46], [49].

Institutionally, existing regulatory frameworks often lack provisions tailored to micro- and pico-scale systems. Licensing and permitting procedures are typically designed for large hydro projects, imposing disproportionate administrative burdens on community developers. Grid interconnection standards are also poorly suited to decentralized systems, constraining opportunities for hybridization or surplus-power sales.

Socio-culturally, community ownership and participatory management require strong local governance, technical capacity, and maintenance support. Limited training has at times led to system downtime or component failure, emphasizing the need for continuous knowledge transfer and spare-parts networks [38].

Beyond these barriers, pico-hydropower has inherent technical limits. Its output is highly site-specific and sensitive to hydrological changes, while its small capacity (≤5kW) mainly suits household-scale loads. Locally built systems may also degrade faster without quality control. Hence, pico-hydro is best applied as a complementary technology within hybrid PV-hydro community systems to improve reliability in off-grid areas.

5.3 Climate and Socio-Environmental Limitations

Climate change poses a growing challenge to the long-term sustainability of pico-hydropower in Southeast Asia. Projected increases in rainfall variability, prolonged dry seasons, and intensified monsoon flooding may disrupt stable generation patterns, causing both underperformance and physical damage to civil structures. Such variability can raise the levelized cost of energy (LCOE) over time by reducing annual generation hours and increasing maintenance frequency.

Under these evolving climatic conditions, hybrid pico-hydro-solar PV configurations may offer improved resilience. Solar PV can complement pico-hydro by providing generation during dry months when streamflow is insufficient, thereby stabilizing electricity supply and reducing lifecycle cost volatility. Integrating such hybrid solutions can enhance system flexibility and strengthen adaptation strategies for future climate scenarios.

Socio-environmental factors also constrain adoption. While community ownership supports local engagement, disputes can arise over land access and water allocation among households and farmers. Transparent consultations, fair benefit-sharing, and recognition of local land and water rights are therefore crucial to ensure equitable and socially accepted pico-hydro deployment in rural areas.

5.4 Opportunities and Co-Benefits

Despite these barriers, pico-hydro offers several unique opportunities that enhance its attractiveness. One major advantage is its synergy with solar PV in hybrid mini grids. Combining the two technologies ensures reliability across seasonal cycles, with hydro providing baseload and PV supplementing during high-demand periods or dry seasons [52]. This hybridization reduces storage requirements, lowering overall system costs.

Another opportunity lies in carbon finance. As demonstrated in Section 4.2, widespread deployment could reduce regional emissions by hundreds of thousands of tons of CO_2 annually. With voluntary carbon markets expanding in Asia, community pico-hydro projects could generate carbon credits, providing additional revenue streams for rural communities [47].

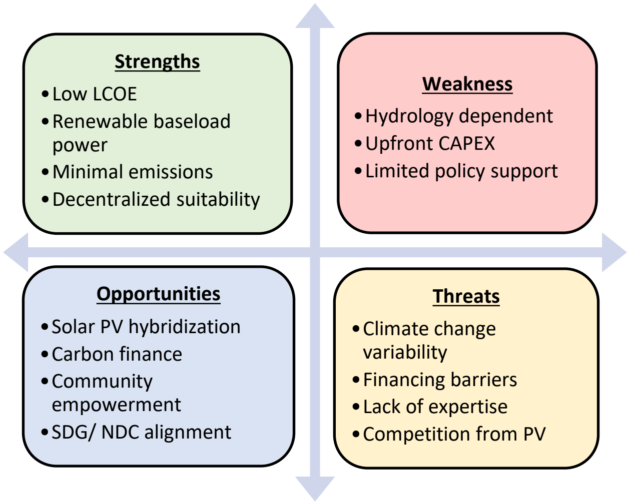

Fig. 6 SWOT analysis of pico-hydro adoption in Southeast Asia.

Beyond economic and environmental metrics, pico-hydro contributes to broader development objectives. Electrified households spend less on kerosene and diesel, freeing resources for education and livelihoods. In Indonesia and the Philippines, pilot projects have shown that reliable electricity enables evening study hours, supports sewing and milling enterprises, and improves healthcare delivery [38-39]. These co-benefits align closely with SDG 4 (Quality Education) and SDG 3 (Good Health and Well-being).

5.5 Regional SWOT Analysis

A regional SWOT analysis was conducted to evaluate the strengths, weaknesses, opportunities, and threats of pico-hydro adoption in Southeast Asia, as illustrated in Figure 6. The analysis identifies key strengths including low LCOE, renewable baseload generation, minimal emissions, and suitability for decentralized deployment.

Weaknesses include dependence on hydrology, high upfront costs, and limited policy support. Opportunities lie in solar hybridization, carbon finance, community empowerment, and alignment with SDG and NDC goals. Threats include climate impacts, financing barriers, skill shortages, and competition from cheaper solar PV. Overall, realizing pico-hydro's potential requires coordinated policies, innovative financing, and local capacity building.

6. Conclusion and Recommendations

This study demonstrates that pico-hydropower is a technically viable and economically competitive option for rural electrification in Southeast Asia. With LCOE values ranging from 0.04 to 0.11 USD/kWh, lower than diesel and comparable to solar PV, it provides continuous baseload generation while avoiding 2-27tCO_2 annually per 5kW system, underscoring its dual economic and environmental benefits [10], [36], [47].

However, scalability remains constrained by hydrological variability, high upfront costs, financing barriers, and limited policy support. Results across six countries indicate that favorable hydrology and strong institutions, as in Lao PDR and Vietnam, lead to lower costs, whereas Myanmar and the Philippines face greater financial and seasonal risks.

Despite relying on published studies for input parameters, this research contributes original findings through a harmonized LCOE-carbon modelling framework applied consistently across six Southeast Asian countries. The study produces new cross-country LCOE results (0.04-0.11 USD/kWh), quantifies annual carbon savings for a typical 5 kW system (23-27tCO_2), and generates regional mitigation estimates not previously published. It also introduces original sensitivity outcomes demonstrating the dominant influence of discount rate and hydrology, and provides new analyses of three financing mixes with their corresponding LCOE and payback periods. These results represent the study's core contribution, offering comparative, policy-relevant evidence that has not been presented in prior pico-hydro literature.

Unlocking pico-hydro's potential requires its explicit inclusion in rural energy plans, simplified licensing for projects under 5MW, and concessional financing through regional or multilateral mechanisms. Strengthening community ownership, technical training, and access to carbon markets, together with solar hybridization, can further improve resilience and viability.

The deployment of pico-hydropower also aligns with ASEAN's broader energy and climate objectives under the APAEC 2021-2025, which targets a 23% renewable share and a 30% improvement in energy efficiency by 2025 [10]. By supporting SDG 7 (Affordable and Clean Energy) and SDG 13 (Climate Action), pico-hydro offers a low-impact, community-driven pathway toward an inclusive and low-carbon energy transition in Southeast Asia.

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