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PHES Site Selection in Sumatra Island, Indonesia Using an Integrated Spatial Screening and AHP-TOPSIS-Based Approach

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Abstract. The rapid growth of variable renewable energy (VRE) increases the need for large-scale energy storage to maintain power system stability. Despite its vast potential, Pumped Hydro Energy Storage (PHES) remains underdeveloped in Indonesia. This study proposes an integrated framework to identify and prioritize PHES sites in Sumatra by combining global data, spatial analysis, and multi-criteria decision-making. From 783 global candidates, 269 sites in Sumatra were identified and further reduced to 4 priority locations through sequential screening. A hybrid Analytical Hierarchy Process (AHP) – Technique for Order of Preference by Similarity to Ideal Solution (TOPSIS) method was applied to rank sites based on technical feasibility, infrastructure accessibility, and environmental risk. The results show that integrating global datasets with structured screening effectively bridges the gap between theoretical potential and practical site selection, providing an approach to support PHES deployment, long-term planning, and knowledge management of Indonesia's State Electricity Company (PLNs) Hydropower Colony.

1 Introduction

Indonesia's transition to Net Zero Emissions requires rapid expansion of renewable energy, particularly variable sources such as solar and wind. However, VRE intermittency challenges grid stability, increasing the need for large-scale, flexible energy storage. Energy Storage Systems (ESS) play a critical role in maintaining reliability through load shifting, peak shaving, and ancillary services. Among available energy storage technologies, PHES has attracted particular attention in Indonesia due to its vast technical potential, estimated at approximately 26,000 candidate sites with a combined storage capacity of up to 821,000 GWh, making it a promising solution for supporting large-scale renewable energy integration [1]. Recent studies in the Indonesian context indicate that PHES can reduce reliance on fuel-based peaking plants and lower generation costs by shifting surplus renewable energy from off-peak periods to periods of high demand [2].

Despite its inclusion in the Electricity Supply Business Plan (RUPTL) 2025–2034, PHES deployment remains limited, with around 4.23 GW planned, far below the estimated national potential of ~1,500 TWh. Although global studies highlight abundant resources [3, 4] development is constrained by engineering, spatial, and socio-environmental factors, leaving Indonesia without a spatially prioritized inventory of feasible PHES sites.

Previous studies have explored various approaches for PHES site selection. A multi-criteria decision-making framework integrating AHP, fuzzy logic, and ÉLimination Et Choix Traduisant la REalité (ELECTRE) III has been proposed to support sustainable site selection, as demonstrated in a case study in Cameroon [5]. More recently, a Geographic Information System (GIS) and AHP-based approach have been applied in Northern Queensland, Australia, incorporating technical and environmental criteria while also evaluating energy costs and carbon emission reduction potential across multiple candidate sites [6].

Existing approaches often focus on methods or specific regions, with limited integration of large-scale datasets and spatial screening for early-stage planning. This study contributes a novel sequential, engineering-informed screening framework that extends conventional AHP–TOPSIS–GIS approaches by integrating global PHES datasets with constructability constraints through the incorporation of engineering proxies, such as reservoir separation and rock excavation volume, at the early stage to eliminate infeasible sites prior to ranking, thereby bridging the gap between global theoretical potential and site-specific practical feasibility.

2 Basic Theory

2.1 Pumped Hydro Energy Storage (PHES)

PHES is a large-scale energy storage technology that converts electrical energy into gravitational potential energy by pumping water from a lower to an upper reservoir during periods of excess supply and releases it through turbines to generate electricity when demand increases. This reversible process enables PHES to balance supply–demand mismatches and support grid stability.

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PHES is the most mature and widely deployed large-scale storage technology, offering high capacity, long operational lifetime, proven reliability, and relatively low cost compared to alternatives. It also provides essential grid services such as load shifting, peak shaving, frequency regulation, and reserve capacity, with a typical round-trip efficiency of 70–85% [3]. The PHES potential sites in Indonesia based on RE100 ANU [7] are presented in Fig. 1.

Fig. 1. The PHES Potential Sites in Indonesia based on RE100 ANU

2.2 Electricity Supply Business Plan (RUPTL)

The RUPTL is the primary planning document for Indonesia's electricity infrastructure development over a ten-year horizon. It defines projections for electricity demand, generation capacity expansion and transmission development.

In the RUPTL 2025–2034, VRE is projected to reach approximately 24 GW. The increasing penetration of VRE in Indonesia's power system necessitates large-scale energy storage solutions such as PHES to maintain system stability and flexibility. A target of 4.23 GW of PHES capacity is planned to be deployed between 2028 and 2033, primarily in Java and Sumatra [8].

2.3 Multi-Criteria Decision Making (MCDM)

Multi-Criteria Decision Making (MCDM) is widely applied in complex infrastructure planning to evaluate alternatives based on multiple, often conflicting criteria [5, 9].

To implement this framework, this study integrates AHP (Fig. 2) to derive the relative importance of criteria, enabling structured decision-making in complex systems [10]. TOPSIS to rank alternatives based on their distance to the ideal solution.

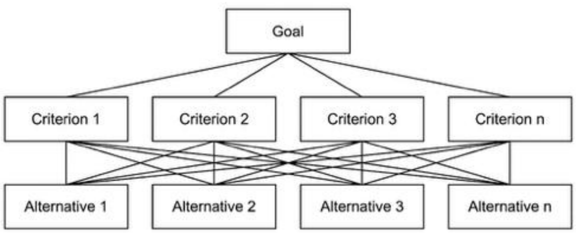

Fig. 2. AHP Structure Template

3 Methodology

The process begins with site identification using the RE100 global atlas, followed by geographic filtering and the application of technical and spatial constraints. While global PHES atlases provide a comprehensive inventory of potential sites, they do not fully capture real-world spatial and socio-environmental constraints. In this context, the integration of GIS-based spatial analysis with AHP has been widely adopted in PHES site selection to incorporate geographic and environmental considerations into decision-making [6].

A hybrid AHP–TOPSIS approach is then applied to prioritize candidate sites, with the results further validated using Quantum Geographic Information System (QGIS) app-based terrain analysis and sensitivity analysis thereby enhancing the robustness of early-stage PHES site selection. The methodology of the research is described in Fig. 3.

3.1 Initial Identification of PHES Candidates from RE100 ANU

The evaluation begins by extracting PHES candidates from the RE100 ANU dataset based on the following initial filters:

- Closed loop, off river Bluefield systems
- Class AAA and AA (lowest cost site)
- Storage capacity 15-500 GWh
- Located in Indonesia

In general, off-river PHES systems are associated with reduced permitting complexity and greater site availability compared to conventional river-based systems [11], providing higher flexibility in meeting evolving power system needs. Meanwhile, the Bluefield system was selected because it utilizes one or two existing reservoirs, such as lakes or dams, thereby ensuring water availability while reducing project complexity and potentially accelerating implementation.

In this context, reservoir separation and dam volume directly influence excavation requirements, construction complexity, and capital expenditure, making them critical parameters in early-stage PHES feasibility assessment [11]. Sumatra Island was selected as the study area due to its favourable mountainous topography and the presence of natural reservoirs, and its strategic role in addressing supply–demand balance and supported by HVDC Sumatra-Java.

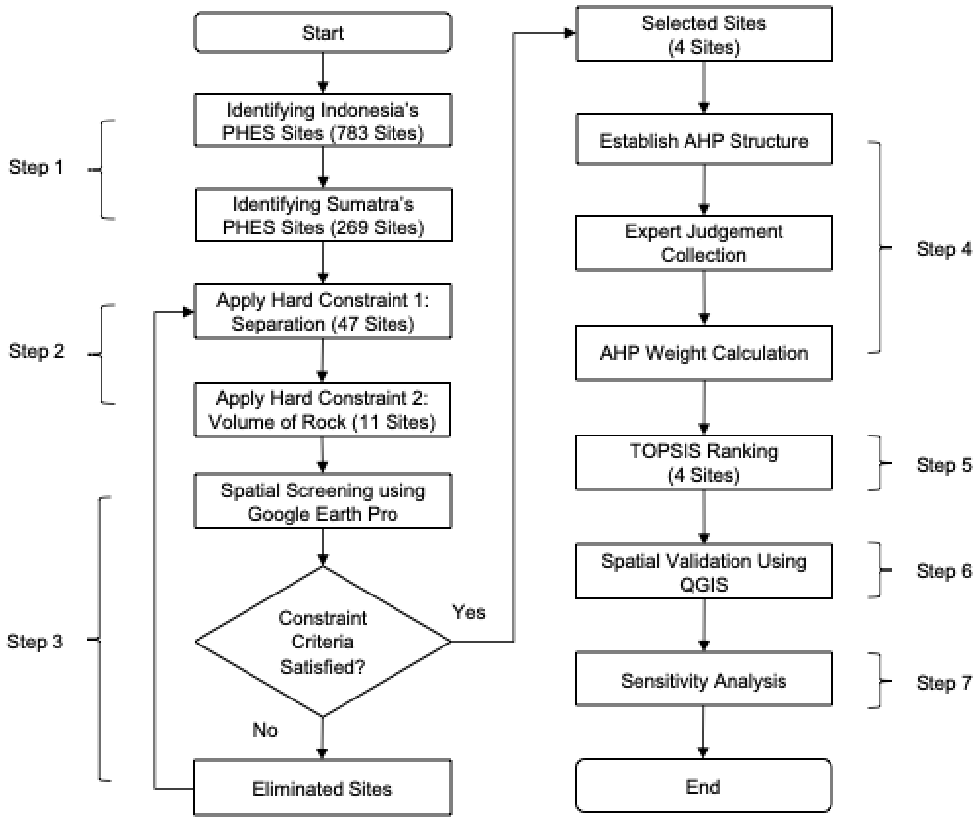

Fig. 3. Methodology of the Research

3.2 Hard Constraint Screening Based on Reservoir Separation and Volume of Rock

While the RE100 ANU provides a comprehensive inventory of potential sites based on techno-economic criteria [1, 9], additional filtering is required to account for construction-related factors that critically influence project implementation. In this context, engineering feasibility is emphasized through the selection of parameters that directly affect constructability, cost, and technical risk. Two key parameters were selected as hard constraints, namely reservoir separation and volume of rock (referred to as "dam volume" in the RE100 ANU dataset).

Reservoir separation determines the length of hydraulic conveyance systems, such as tunnels and penstocks, and thus strongly influences construction cost, underground engineering complexity, and project/ social risk. A maximum threshold of 4 km is adopted based on practical experience in PHES development in Indonesia, where longer distances tend to significantly increase tunnelling requirements, construction duration, and associated uncertainties, while also expanding the project footprint and potential social exposure.

Meanwhile, volume of rock represents the excavation requirement and serves as a proxy for the magnitude of civil works. Larger excavation volumes are associated with higher construction costs, increased geotechnical risks, longer construction time, and greater implementation uncertainty. In this study, a maximum threshold of 2 GL is applied as a practical filtering criterion, with the objective of reducing the candidate pool to a manageable range of approximately 10–15 sites for further evaluation. This threshold prioritizes sites with lower excavation demand, which are generally more favourable in terms of constructability, cost efficiency, and risk mitigation.

The general PHES configuration, highlighting reservoir separation and additional excavation volume of rock is illustrated in Fig 4 as follows.

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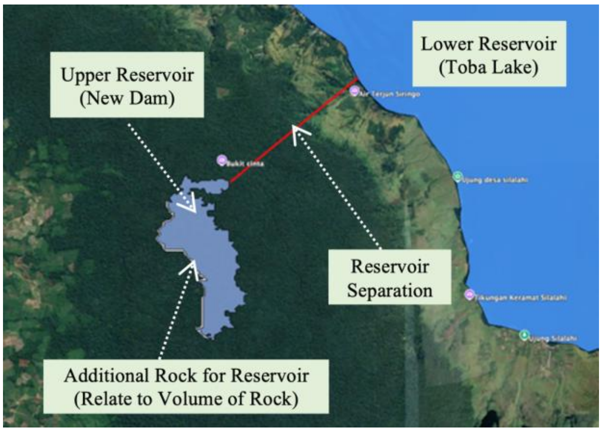

Fig. 4. General Configuration of PHES

3.3 Spatial Screening & Evaluation

A spatial evaluation using Google Earth Pro is conducted to assess PHES feasibility by incorporating geographic, environmental, and social factors. Initial verification using satellite imagery confirms existing water bodies (Bluefield classification).

Hard constraints, such as insufficient elevation difference, overlap with settlements, indigenous areas, or fault lines, are used to eliminate infeasible sites. Remaining sites are evaluated using soft constraints, including proximity to sensitive areas, roads, and transmission lines to reflect accessibility and grid integration.

3.4 Establishment of Criteria and Sub-Criteria

A structured AHP framework is applied to evaluate PHES candidate sites, comprising three main criteria and eight sub-criteria (Table 1).

A questionnaire survey of 24 hydropower and renewable energy experts was conducted to derive criterion weights through pairwise comparisons using the Saaty scale. AHP analysis involved matrix normalization and eigenvector-based weight calculation, with consistency verified (CR < 0.1). After collecting expert judgments through questionnaires, the geometric mean method was applied to aggregate individual assessments into a single representative pairwise comparison matrix. The resulting weights were used as inputs for subsequent TOPSIS-based site ranking.

Table 1. Criteria and Sub-Criteria within AHP

No	Criteria	Sub-Criteria
1	Technical & Topographical Feasibility (A)	Head (A1)
		Separation (A2)
		Volume of Rock (A3)
2	Infrastructure & Grid Accessibility (B)	Proximity to Road (B1)
		Proximity to Power Network (B2)
3	Environmental, Social & Geological Risk (C)	Proximity to Indigenous Communities (C1)
		Proximity to Communities (C2)
		Proximity to Earthquake Fault (C3)

3.5 Site Ranking using TOPSIS

PHES sites are ranked with the TOPSIS method. A weighted normalized matrix is constructed, followed by identification of ideal and anti-ideal solutions. Each site's relative closeness coefficient is then calculated, with higher values indicating greater suitability.

3.6 Spatial Validation using QGIS

Spatial validation was performed using QGIS based on Digital Elevation Model (DEM) data obtained from the official Indonesian geospatial portal [12].

Longitudinal profile analysis is used to assess the elevation difference between the upper and lower reservoirs and to ensure alignment with the head values provided in the RE100 ANU dataset. In addition, cross-sectional analysis is conducted to identify terrain features such as natural topographic depressions that may support reservoir development.

3.7 Sensitivity

Sensitivity analysis is conducted to evaluate the robustness of the site ranking results against variations in criteria weights derived from expert judgment. To address the inherent subjectivity of AHP, a proportional and stable weight adjustment approach is applied, where the weight of a selected criterion is varied within a range of ±30%, while the remaining criteria are proportionally redistributed based on their original ratios. For each scenario, the updated weights are used to recompute the TOPSIS ranking.

4 Results and Discussion

4.1 Identification of PHES Potential

Initial screening using the PHES Shortlisting Tool available on the RE100 website, using the initial filter criteria successfully identified 783 candidate PHES locations across Indonesia. Filtering for Sumatra Island reduced this dataset to 269 locations. These locations constitute the initial dataset used for subsequent spatial filtering and technical evaluation in this study.

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4.2 Preliminary Site Selection Based on Hard Constraints

The application of a maximum reservoir separation of 4 km reduces the candidate pool to 47 sites, indicating that many initially identified locations would require extensive tunnelling and complex hydraulic infrastructure.

The application of the volume of rock constraint (maximum 2 GL), aimed at obtaining a manageable dataset, further reduces the candidate pool to 11 sites, highlighting the strong sensitivity of feasibility to excavation requirements.

4.3 Spatial Verification Using Satellite Imagery

Preliminary spatial verification using satellite imagery confirmed the presence of existing lakes or reservoirs, ensuring compliance with the Bluefield classification. Sites with insufficient elevation differences or overlapping with residential areas, indigenous communities, or earthquake fault lines were treated as hard constraints and excluded, significantly reducing viable candidates. The nearest substations were then identified, and all parameters, including those previously applied as hard constraints, were re-evaluated using distance-based metrics as soft constraints.

Of the 11 sites remaining after hard-constraint screening, seven were excluded during spatial verification due to insufficient elevation differences, overlap with settlements or indigenous communities, proximity to active fault lines, or the absence of suitable existing reservoirs required for the Bluefield configuration.

This process yielded four candidate sites that satisfied all screening criteria and were subsequently evaluated using the AHP–TOPSIS framework, with the results further validated through QGIS-based spatial verification and sensitivity analysis. All four candidate sites are in Samosir Regency, North Sumatra Province. Site 1 is situated in Tanjungan Village, Simanindo District; Site 2 in Silalahi I Village, Sumbul District; while Sites 3 and 4 are in Salaon Dolok Village, Ronggur Nihuta District. Importantly, all identified sites are located around Lake Toba, enabling the lake to function as the lower reservoir and thereby fulfilling the key requirement of a Bluefield PHES system.

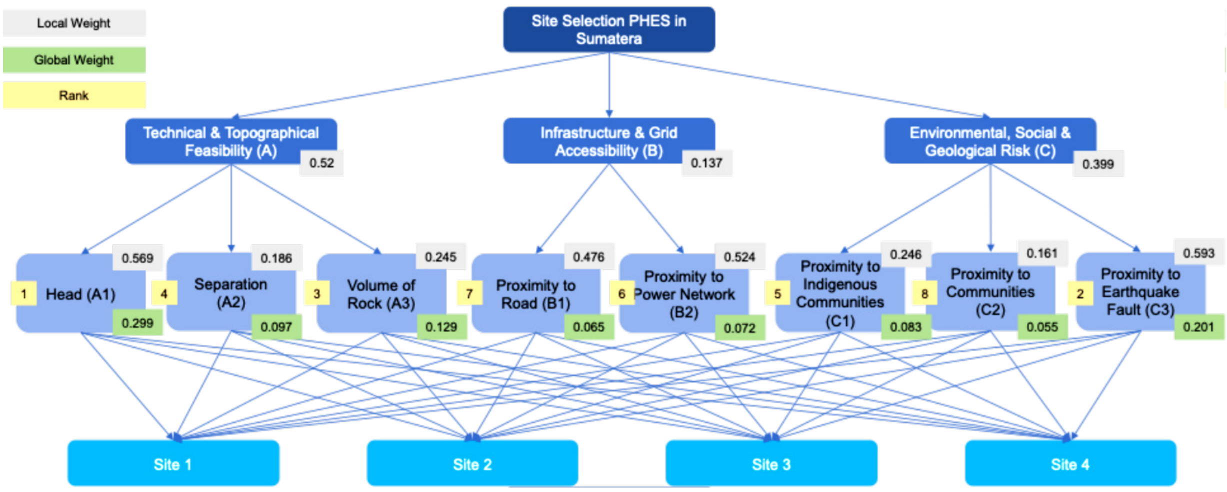

Fig 5. AHP Structure and Weighting Outcomes

Table 2. The summary of the four sites selected

No	Parameter	Unit	Site 1	Site 2	Site 3	Site 4
1	Head (A1)	meter	611,00	760,00	695,00	691,00
2	Separation (A2)	kilometre	2,50	2,70	3,50	3,50
3	Volume of Rock (A3)	Giga litre	0,20	1,30	0,90	0,60
4	Proximity to Road (B1)	kilometre	1,52	6,21	1,38	0,78
5	Proximity to Power Network (B2)	kilometre	23,23	2,04	13,31	18,00
6	Proximity to Indigenous Communities (C1)	kilometre	2,77	19,74	6,18	6,46
7	Proximity to Communities (C2)	kilometre	0,03	0,65	0,08	0,05
8	Proximity to Earthquake Fault (C3)	kilometre	21,14	15,00	27,11	25,35

4.4 Analytical Hierarchy Process (AHP)

AHP results (Fig. 5) show Technical and Topographical Feasibility (A) as the dominant criterion (0.525), followed by Environmental and Geological Risk (C) (0.339) and Infrastructure Accessibility (B) (0.137). At the sub-criteria level, head (A1) is the most influential (0.299), followed by proximity to fault lines (0.201) and rock volume (0.129), while other factors have moderate to lower influence. All consistency ratios (CR < 0.1) confirm reliable judgments, highlighting technical performance and geological safety as key drivers in PHES site selection.

4.5 TOPSIS-Based Site Ranking

From an engineering perspective, the energy storage capacity of PHES can be approximated using E=ρ.g.h.V, indicating a linear relationship with head and highlighting the importance of topography in system performance.

TOPSIS was applied to rank the candidate sites based on the parameters presented in Table 2, considering their distances from the ideal and negative ideal solutions, as shown in Fig. 6 and Table 3. The results indicate that Site 2 ranks highest (Ps = 0.68), outperforming all other alternatives.

Table 3. TOPSIS Distance Measures and Ranking Results

Alternatives	Ed+	Ed-	Ps	Rank
Site 1 (S1)	0.13	0.14	0.51	4
Site 2 (S2)	0.07	0.16	0.68	1
Site 3 (S3)	0.09	0.15	0.61	2
Site 4 (S4)	0.11	0.14	0.57	3

This is primarily driven by the dominant weight of technical feasibility (0.525), particularly head (0.299), where Site 2 has the highest value (760 m). Its performance is further supported by the shortest distance to the power network (2.04 km), enhancing infrastructure accessibility.

Despite its higher dam volume and closer proximity to communities, the relatively lower weights assigned to these criteria limit their influence on the final ranking. Site 2's top ranking is driven by highly weighted factors, head and infrastructure accessibility, making it the most suitable PHES candidate based on the established decision criteria.

This advantage is further reinforced from an engineering and economic perspective. The higher head of Site 2 increases energy density, enabling greater energy generation per unit of stored water, while reducing the required reservoir volume and associated civil works. This leads to lower capital expenditure (CAPEX). In general, higher-head PHES systems tend to achieve lower specific costs (USD/kWh) due to more efficient water utilization and reduced infrastructure requirements, highlighting head as a key parameter influencing both technical and economic feasibility.

4.6 Spatial Validation

The validation results of Site 2 further confirmed the feasibility of the selected PHES sites. Longitudinal profile analysis shown in Fig. 7 demonstrated elevation differences between the upper (1757 m ASL) and lower reservoirs (835 m ASL) that are consistent with the head values reported in the ANU dataset, indicating the reliability of the dataset for preliminary assessment.

In addition, cross-sectional analysis revealed the presence of natural topographic depressions (1671 to 1694 m ASL) at the proposed upper reservoir locations, suggesting favourable conditions for the development of artificial upper dams. These findings provide additional confidence that the selected sites are technically viable for further PHES development studies.

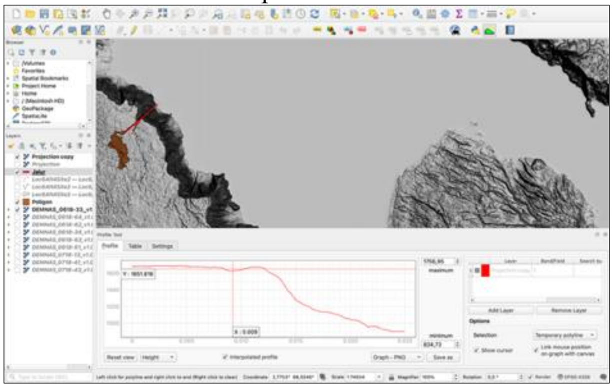

Fig. 6. Longitudinal Profile Validation Using QGIS Along the Tunnel Between the Reservoir Dams

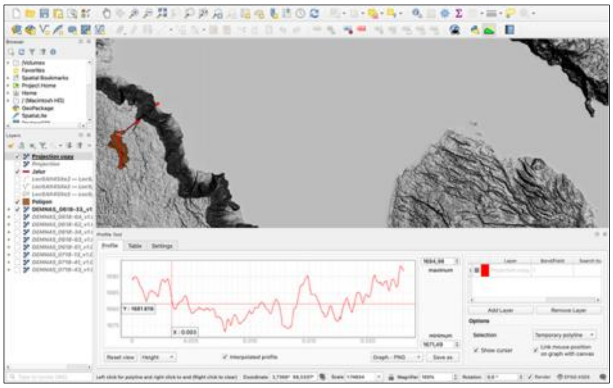

Fig.7. Longitudinal Profile Validation Using QGIS Within the Proposed Upper Dam

4.7 Sensitivity Analysis

The sensitivity analysis results (Table 4) confirm a high level of robustness in the PHES site rankings with the variations up to ±30%. Variations in the Technical and Topographical Feasibility criterion (A) did not affect the ranking, with Site 2 consistently maintaining the top position, indicating low sensitivity to changes in the dominant criterion. This stability is primarily attributed to its hydraulic head of 760 m, the highest among all candidates, and its proximity to the power network (2.04 km) which together provide significant advantages in energy storage potential and grid integration. In addition, Site 2 is located farthest from earthquake fault line (15,00 km), indigenous community (19,74 km), and community (0,65 km), thereby reducing potential fault, social and land-use conflicts.

For Infrastructure and Grid Accessibility (B), the results show minimal impact on ranking, suggesting that all candidate sites have relatively comparable connectivity, making this criterion less decisive. Meanwhile, Environmental and Geological Risk (C) exhibits moderate sensitivity but does not alter the ranking structure, indicating no extreme risk differences among the sites.

Ranking changes occur only under the unrealistic equal-weight scenario, while Site 2 remains unaffected. Overall, the results confirm the robustness and reliability of the proposed AHP–TOPSIS framework supporting confidence in the final site selection outcome.

Table 4. Sensitivity Analysis

Criteria	Test Value	Rank			
		S1	S2	S3	S4
Technical & Topographical Feasibility (A) Initial Weight: 0,525	-30%	4	1	2	3
	-20%	4	1	2	3
	-10%	4	1	2	3
	10%	4	1	2	3
	20%	4	1	2	3
	30%	4	1	2	3
Infrastructure & Grid Accessibility (B) Initial Weight: 0,137	-30%	4	1	2	3
	-20%	4	1	2	3
	-10%	4	1	2	3
	10%	4	1	2	3
	20%	4	1	2	3
	30%	4	1	2	3
Environmental, Social & Geological Risk (C) Initial Weight: 0,339	-30%	4	1	2	3
	-20%	4	1	2	3
	-10%	4	1	2	3
	10%	4	1	2	3
	20%	4	1	2	3
	30%	4	1	2	3
Equal Weight Scenario (A: 0,334; B: 0,333; C: 0,333)		2	1	3	4

5 Conclusion

This study proposes an integrated framework for identifying and prioritizing potential PHES sites in Sumatra by combining global atlas datasets, spatial screening, and multi-criteria decision-making methods. The sequential screening process effectively reduced candidate sites from 783 locations across Indonesia to 269 in Sumatra, 47 meeting the reservoir separation constraint, 11 satisfying the dam volume constraint, and finally 4 sites after spatial filtering. All four shortlisted sites utilize Lake Toba as the lower reservoir, while new upper reservoirs are proposed at elevated locations, thereby representing practical Bluefield PHES configurations with reduced water availability risks and lower environmental impacts compared with conventional river-based schemes.

The hybrid AHP–TOPSIS approach enabled systematic ranking based on technical feasibility, infrastructure accessibility, and environmental risk, while QGIS-based validation further confirmed the feasibility of the selected sites. However, the findings should be interpreted with several limitations. The analysis relies on secondary datasets and spatial tools, without detailed geological, hydrological, or techno-economic assessments. The results are also subject to methodological uncertainty associated with expert-based weighting and input assumptions, despite the robustness indicated by sensitivity analysis. Future research should incorporate field investigations and comprehensive techno-economic analysis to further validate the results.

Overall, the results identify several locations in Sumatra as technically and practically viable for PHES development. The proposed methodology offers a systematic and replicable approach for early-stage site identification, supporting future feasibility studies and long-term electricity planning, including potential integration into the RUPTL. This study also highlights the importance of spatially informed screening to avoid overestimating technically feasible but impractical projects. Ultimately, it bridges the gap between theoretical potential and practical development, while demonstrating that spatial and land-use constraints can critically influence PHES feasibility and should be integrated into site selection frameworks.

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