

Research Article

Economic and Socio-Environmental Benefits of Utilizing Existing Reservoirs for Brownfield Pumped Storage Development in Indonesia

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Abstract Pumped storage hydropower (PSH) is a critical technology for supporting renewable energy integration and long-duration energy storage. In Indonesia, where numerous multipurpose reservoirs already exist, brownfield PSH—developed by reusing an existing lower reservoir—offers a promising alternative to conventional greenfield construction. This study evaluates the economic and socio-environmental benefits of brownfield PSH using the Upper Cisokan Pumped Storage (UCPS) project as a representative reference case. A two-stage methodology is applied, consisting of a global literature review and a quantitative economic assessment based on engineering and cost data from the UCPS Project Appraisal Document.

The analysis demonstrates that brownfield PSH significantly reduces new land disturbance, environmental impacts, and social disruption by eliminating the need for a new lower reservoir. Using the Height × Area method to allocate dam construction costs, the avoided lower-dam civil works amount to US\$90.14 million. Reuse of an existing reservoir also reduces land acquisition and resettlement requirements, yielding an additional saving of US\$56.9 million. Furthermore, removing the lower-dam construction shortens the critical-path schedule by 18 months, resulting in US\$33.36 million in avoided indirect EPC costs and US\$8.98 million in reduced interest during construction. In total, brownfield development provides an estimated economic benefit of US\$189.38 million, equivalent to approximately 25% of total project cost.

Beyond economic gains, brownfield PSH yields substantial socio-environmental advantages, including reduced habitat loss, fewer resettlement pressures, lower permitting risk, and minimal riverine impacts due to closed-loop configurations. These findings highlight the strong potential of reservoir-based brownfield PSH as a sustainable and cost-effective pathway for advancing Indonesia's energy-storage infrastructure.

Keywords: *Pumped-storage, Socio-Environmental, Reservoir, Economics, Sustainability*

1. Introduction

The increasing penetration of variable renewable energy sources—particularly solar and wind—has heightened the need for reliable large-scale energy storage to maintain power system stability. Pumped Storage Hydropower (PSH) remains the most mature and widely deployed long-duration storage technology globally, accounting for more than 90% of grid-scale storage capacity [1]. As countries move toward higher shares of

renewables, PSH has regained strategic importance due to its flexibility, fast-response capability, and ability to mitigate intermittency [2].

Recent global studies highlight a shift from conventional *greenfield* PSH development toward *brownfield* approaches that reuse existing reservoirs or post-industrial sites. Brownfield PSH has gained attention because it reduces land disturbance, minimizes environmental and social impacts, and lowers overall project costs—particularly by avoiding the construction of a new lower reservoir [3] [4]. Despite these benefits, the majority of PSH literature still focuses on greenfield development, leaving a gap in quantitative assessments of brownfield potential, especially in developing countries.

In Indonesia, challenges such as high capital requirements, extensive land acquisition, and social–environmental risks have slowed the deployment of new PSH facilities. At the same time, Indonesia possesses a large portfolio of multipurpose reservoirs managed by the Ministry of Public Works and Housing (PUPR), providing significant opportunities for brownfield PSH development—yet systematic evaluations of their economic and socio-environmental benefits remain limited.

Addressing this research gap, the present study analyzes the economic and socio-environmental advantages of brownfield PSH compared with greenfield development. Using technical, financial, and land-acquisition data from the Upper Cisokan Pumped Storage (UCPS) project, the study quantifies cost savings, reduced land requirements, and construction-time benefits derived from using an existing reservoir as the lower basin. By integrating literature review findings with a detailed case-based economic assessment, this research provides new insights into the viability of reservoir-based PSH development and its strategic role in Indonesia’s energy transition.

2. Materials and methods

This study applies a two-stage methodology consisting of a literature review and an economic assessment to evaluate the comparative benefits of brownfield pumped storage hydropower (PSH) using existing reservoirs in Indonesia.

2.1. Literature Review

The first stage reviews international experiences with brownfield and retrofitted PSH projects, particularly in Japan, Europe, and China. The review identifies key differentiators between brownfield and greenfield development, focusing on:

- Environmental aspects (land use, ecosystem impacts, water-resource changes), and
- Social aspects (land acquisition, resettlement, and community impacts).

These factors establish the conceptual basis for assessing how reusing existing reservoirs reduces the environmental and social footprint of PSH development.

2.2. Economic Assessment

The second stage quantifies the economic advantages of brownfield PSH. The analysis uses the Upper Cisokan Pumped Storage (UCPS) project as the reference case, drawing on its engineering design, cost structure, land-acquisition requirements, and construction schedule as provided in the World Bank Project Appraisal Document [6]. UCPS is selected because it is the only Indonesian PSH project with complete and publicly available technical and financial documentation.

The economic assessment examines three categories of brownfield benefits:

1. Avoided lower-dam construction cost,
2. Avoided land-acquisition and resettlement cost, and
3. Schedule-related savings resulting from reduced construction duration.

2.3. Cost Allocation Method

UCPS reports the Upper and Lower Dams as a combined cost item. To isolate the lower-dam portion—representing the avoided cost in a brownfield scenario—this study applies the Height × Area method, which allocates cost in proportion to dam height and reservoir surface area. This method best reflects structural effort and is consistent with hydropower engineering practice. Alternative methods were considered but not adopted due to weaker alignment with construction cost drivers.

2.4. Scope and Limitations

All quantitative results are based on the specific characteristics of UCPS, including its topography, dam geometry, and local compensation structure. Thus, the findings represent site-specific case estimates, although the methodology itself is transferable to other PSH locations.

3. Results and discussion

3.1. Techno-Socio-Benefits of Brownfield PSH Compared to Greenfield PSH

The decision to develop pumped storage hydropower (PSH) on a brownfield or greenfield site not only influences the extent of land transformation but also shapes the overall construction strategy and associated impacts [7]. Brownfield PSH developments—particularly those that reuse an existing reservoir as the lower basin—offer several notable techno-socio-environmental advantages over greenfield alternatives.

1) Substantially Lower New Land Disturbance and Habitat Loss

Multiple studies demonstrate that brownfield PSH results in significantly lower environmental disturbance due to the reduced need for new excavation and inundation. Greenfield PSH exhibits approximately 30% higher Global Warming Potential (GWP) than brownfield PSH because greenfield schemes require construction of both upper and lower reservoirs, resulting in greater earthworks and land-use change [3]. In contrast, brownfield projects tend to require only a new upper reservoir while reusing existing storage for the lower basin, which limits additional impacts.

The Joint Research Centre [4] also documents that upper reservoirs in brownfield retrofits typically range between 0.4–1.5 km², whereas greenfield PSH schemes often require 4–20 km² of new inundated area to construct both reservoirs [5]. This corresponds to an approximate 63–98% reduction in newly inundated area, depending on site configuration.

The environmental advantages of brownfield PSH arise from:

- Lower ecological impact: Reusing pre-disturbed basins avoids the flooding of natural valleys and minimizes habitat alteration [8].
- Minimal surface disruption: Brownfield locations—such as mining pits or existing reservoirs—provide pre-existing storage volume, reducing earthworks and avoiding major environmental disturbance [8].
- Use of previously disturbed land: Since brownfield areas have already undergone land clearing and industrial activity, additional environmental impacts are significantly

reduced, and existing infrastructure (roads, transmission lines, water access) can often be reused.

Collectively, these findings indicate that brownfield PSH is strongly preferable for minimizing GWP, land-use change, and habitat loss [8].

2) Reduced Civil Works and Lower Embodied Environmental Impacts

Civil works account for the majority of the environmental footprint of PSH development, including excavation, dam construction, tunneling, powerhouse works, switchyard structures, and access roads. Brownfield PSH schemes benefit from existing infrastructure such as dams, benches, haul roads, and water management systems, reducing the need for extensive new construction.

Case studies such as the Kidston pumped-hydro project demonstrate that reusing existing structures significantly decreases the volume of concrete, earthworks, and auxiliary civil works required for new PSH facilities [9] [10]. Consequently, brownfield development can reduce construction-related emissions, cost risks, and schedule uncertainty associated with major dam-building activities.

3) Smaller Social Footprint: Reduced Resettlement and Land-Use Conflict

Brownfield PSH sites—particularly existing reservoirs and abandoned mining sites—typically involve minimal new community displacement because the land has already been inundated or disturbed. This contrasts sharply with greenfield reservoirs, which commonly require:

- New land acquisition,
- Resettlement of households,
- Compensation processes, and
- Negotiation of land-use rights.

Experiences from the Kidston project and transmission corridor planning show that brownfield schemes face fewer social barriers and lower risks of community opposition [9] [11]. Similarly, reservoir-repurposing studies [4] confirm that converting existing impoundments into PSH systems avoids most resettlement challenges associated with greenfield dam construction.

4) Lower Permitting Risk and Faster Approvals

Regulatory processes for brownfield PSH projects are often less complex because:

- hydrological baselines are already established,
- water licenses may already exist,
- environmental impact zones are well understood, and
- pre-disturbed areas typically have lower ecological sensitivity.

As shown in project assessments from Australia and recent PSH environmental reviews, brownfield sites experience faster environmental approvals and reduced permitting uncertainty compared with greenfield river-damming projects [2] [10].

3.2. Economic Benefits of Brownfield Compared to Greenfield PSH

This section quantifies the economic advantages of brownfield pumped storage hydropower (PSH) relative to a greenfield configuration, using the Upper Cisokan Pumped Storage (UCPS) project as the reference case. The analysis evaluates three major categories of avoidable cost in a brownfield scenario: (1) direct civil-works savings from avoiding construction of the lower dam, (2) reduced land-acquisition and resettlement expenditure, and (3) schedule-related cost savings arising from shorter construction duration.

1) Direct Civil-Works Savings: Avoided Lower-Dam Construction

Because dam construction cost is largely driven by structural volume, foundation treatment, and spillway scale, this study allocates the UCPS “Upper and Lower Dams” cost item (US\$111.51

million) using a Height \times Area proxy. This method multiplies each dam's structural height by its reservoir surface area to approximate relative construction effort and material requirement—an approach consistent with hydropower engineering cost drivers.

For UCPS, the lower dam has a height of 98 m and a reservoir area of 2.60 km², yielding a score of:

$$98 \times 2.60 = 254.8.$$

The upper dam has a height of 75.5 m and an area of 0.80 km², giving:

$$75.5 \times 0.80 = 60.4.$$

The lower dam therefore accounts for:

$$\frac{254.8}{254.8 + 60.4} = 0.8084 \approx (80.84\%)$$

Applying this proportion to the combined dam cost:

$$111.51 \text{ M} \times 0.808 = 90.14 \text{ Million USD},$$

which represents the direct civil-works expenditure avoided in a brownfield configuration where the lower reservoir already exists. This aligns with observations from recent assessments that at least one major reservoir cost can be eliminated in brownfield PSH development [2].

2) Reduced Land Acquisition and Resettlement Cost

The UCPS land-acquisition plan identifies a total required area of 363.46 ha, covering reservoir inundation, a switchyard, slope-stability buffers, disposal sites, and green belts [6]. From the ESIA, the combined reservoir footprints are:

- Lower reservoir: 260 ha
- Upper reservoir: 80 ha

Total: **340 ha**, leaving **23.46 ha** as ancillary land for non-reservoir purposes.

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- Lower reservoir: 260 ha
- Upper reservoir: 80 ha

Total: 340 ha, leaving 23.46 ha as ancillary land for non-reservoir purposes.

Because buffer zones and hazard areas scale with reservoir perimeter and footprint, this ancillary land is allocated proportionally to each reservoir's area. The lower reservoir accounts for:

$$\frac{260}{340} = 0.7647.$$

Thus, the lower reservoir receives:

$$23.46 \times 0.7647 = 17.94 \text{ ha}.$$

The total lower-basin land requirement is therefore:

$$260 + 17.94 = 277.9 \text{ ha}.$$

Applying the UCPS land budget of US\$74.40 million proportionally yields an avoided land-acquisition cost of approximately:

$$74.40 \text{ M} \times \frac{277.9}{363.46} \approx 56.9 \text{ Million USD}.$$

This saving reflects the reduced need for land procurement and resettlement when an existing reservoir is utilized in a brownfield scheme

3) Schedule-Related Cost Savings from Reduced Construction Duration

In the greenfield configuration, the UCPS lower dam requires 50 months to construct, while the upper dam requires 32 months, with both structures executed in parallel. The lower dam therefore determines the 50-month critical path. In a brownfield configuration, the lower dam is no longer required, reducing the critical-path duration to 32 months. This results in a schedule reduction of:

$$50 - 32 = 18 \text{ months} \approx 1.5 \text{ years}$$

A shorter construction period directly reduces time-dependent expenditures, including contractor overhead, site management, temporary works, camp operations, supervision, and equipment standby. To quantify this, the share of civil works avoided is calculated as:

$$\frac{90.14}{291.55} = 0.3092,$$

using the civil-works baseline of US\$291.55 million.

International hydropower benchmarks estimate that time-dependent indirect EPC components represent approximately 37% of direct civil-works cost [12] This yields:

$$291.55 \text{ M} \times 0.37 = 107.88 \text{ M USD.}$$

Scaling this by the avoided share gives:

$$107.88 \text{ M} \times 0.3092 = 33.36 \text{ Million USD,}$$

representing the indirect EPC overheads avoided in the brownfield scenario.

The UCPS PAD allocates US\$35.91 million to Interest During Construction (IDC) over a 72-month financing period. An 18-month reduction proportionally reduces IDC by:

$$35.91 \text{ M} \times \frac{18}{72} = 8.98 \text{ Million USD.}$$

Combining these yields total schedule-related savings of:

$$33.36 \text{ M} + 8.98 \text{ M} = 42.34 \text{ M USD.}$$

When viewed against the total UCPS project cost of US\$762.56 million, the brownfield savings of US\$189.38 million represent a reduction of approximately 24.8% of overall investment.

Table 1 presents the estimated total economic savings obtained from developing a brownfield pumped-storage hydropower (PSH) project compared with a greenfield configuration.

Table 1. Estimated Economic Benefits of Brownfield Pumped-Storage Development Utilizing Existing Dams

Economic Benefit	Description	Estimated Savings (USD M)
Civil Works Savings	Avoided construction of a new lower dam	90.14
Land Acquisition & Resettlement Savings	Reduced land requirements due to the use of existing reservoirs	56.90
Savings from Shortened Construction Duration (1.5 years)	Avoided time-related costs, including overhead, site management, temporary facilities, and supervision	33.36
	Interest During Construction (IDC) Savings	8.98
Total Economic Benefits		189.38

Source: Author's Analysis

4. Discussion

Overall, the literature and case studies consistently demonstrate that brownfield pumped storage hydropower (PSH) offers substantial sustainability advantages over greenfield development. By reusing existing reservoirs or previously disturbed land, brownfield PSH significantly reduces new land disturbance, minimizes habitat loss, and lowers embodied environmental impacts associated with major civil works. These projects also impose a smaller social footprint, requiring far less land acquisition and resettlement while avoiding many of the conflicts commonly associated with new reservoir construction. Furthermore, brownfield PSH typically faces lower permitting and regulatory risk, benefits from existing infrastructure.

Taken together, these techno–socio–environmental advantages position brownfield PSH as a more sustainable and socially acceptable strategy for expanding long-duration energy storage, particularly in regions where suitable existing basins or post-industrial sites are available for repurposing.

The economic analysis demonstrates that brownfield pumped storage hydropower (PSH), which reuses an existing reservoir, provides substantial cost advantages compared with a greenfield configuration. For a project of UCPS scale, the principal economic gains arise from avoided lower-dam construction (US\$90.14 million) and the elimination of significant land-acquisition and resettlement needs (US\$56.90 million). Additional savings are achieved through reduced construction duration, yielding lower time-dependent EPC expenditures (US\$33.36 million) and reduced interest during construction (US\$8.98 million). Collectively, these components amount to a total economic benefit of approximately US\$189.38 million, representing about 25% of total project cost. These results underscore the economic viability of brownfield PSH and highlight the financial value of repurposing existing reservoirs to support Indonesia's long-duration energy storage needs.

Author contributions: The authors contributed to this work as follows: Rechman Sinurat was responsible for conceptualization and methodology. Formal analysis was conducted by Rechman Sinurat, Ria Lubis, and Ardian Inkaresa. Investigation activities were carried out by Rechman Sinurat and Ria Lubis, while data curation was performed by both Rechman Sinurat and Ria Lubis. The original draft of the manuscript was prepared by Rechman Sinurat and Ria Lubis, and the review and editing process involved Rechman Sinurat, Ria Lubis, and Ardian Inkaresa. Visualization was completed by Rechman Sinurat. Supervision was provided by Ardian Inkaresa, and project administration was undertaken by Rechman Sinurat. All authors have read and approved the final version of the manuscript.

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Conflict of interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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