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Techno-economic assessment of floating photovoltaic integration in cascaded hydropower reservoirs: A case study in Laos

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Abstract
Floating photovoltaic (FPV) systems on hydropower reservoirs can improve the generation of renewable energy by avoiding land use and reducing reliance on hydropower. However, the majority of previous FPV–hydropower studies focus on stand-alone reservoirs rather than cascaded systems with inter-plant hydraulic and electrical interactions. The objective of this paper is to assess the technical and economic performance of coordinated FPV integration in the Nam Kong 2 (NK2)–Nam Kong 3 (NK3) cascade in southern Laos, and to identify practical deployment options that preserve energy export capacity and improve water management. Hourly FPV generation data was simulated with hourly hydro generation and daily reservoir storage with a coordinated dispatch model respecting plant-level limits, a shared export constraint, and cascade routing between the reservoirs. FPV layouts were tested against performance indicators such as export adequacy, solar utilisation, water saving, water spill, and economic viability. The results reveal that not all FPV configurations improve the cascade performance. Large upstream FPV deployment at NK3 increases curtailment and reduces downstream support to NK2, resulting in higher export deficits. In contrast, downstream-only or downstream-dominant FPV layouts maintain export adequacy more effectively and provide more meaningful cluster water savings. The results suggest that FPV placement within the cascade is more important than simply increasing total installed FPV capacity. The paper recommends grid-aware and cascade-aware FPV sizing, with emphasis on downstream deployment or really limited upstream deployment where maintaining release support is critical.

Keywords: Floating photovoltaic; Cascaded hydropower; Coordinated dispatch; FPV–hydropower integration; Techno-economics.

1. Introduction
Floating photovoltaic (FPV) systems represent an innovative solution that addresses land scarcity and helps manage water resource (Kakoulaki et al., 2023; Solomin et al., 2021). FPV technology can generate electricity without land use, save water through evaporation mitigation, and improve panel efficiency through the natural cooling effects from water surfaces (Hao et al., 2025). FPV integration with hydropower helps mitigate the effects of seasonal water variability, particularly during dry seasons, and improve utilisation of existing infrastructure (Kimura et al., 2025; Nahar et al., 2024; Nhiavue et al., 2022). Studies also suggest that modest reservoir coverage can produce significant gains. For example, coverage of about 10% can increase generation substantially, while larger coverage levels can further enhance water conservation and energy yield, yet with increasing technical, ecological and economic feasibility uncertainties (Haas et al., 2020; Kimura et al., 2024).

Despite substantial literature on FPV–hydropower integration, a limitation remains. The majority of the FPV–hydropower studies remain focused on individual reservoirs. By contrast, studies on cascade hydropower, despite developed sophisticated approaches to multi-reservoir scheduling, inter-plant coordination and stochastic water management, have not effectively addressed FPV integration in cascaded hydropower systems (Giuliani et al., 2021; Kangrang et al., 2023; Li et al., 2025; Soomro et al., 2023; Zhou et al., 2021).

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This gap matters given that cascaded reservoirs are hydraulically and, at times, electrically linked. Upstream solar substitution may conserve water locally, altering downstream water inflow, spill, release timing and shared-grid performance. Lacking proper understanding of these inter-plant interactions would prevent a reliable assessment of FPV's contribution to basin-scale water–energy management.

Lao PDR provides a particularly relevant context for cascaded FPV–hydropower integration. The country relies heavily on hydropower for domestic supply and regional electricity exports, yet this dependence also exposes the power sector to strong seasonal water variability during the dry season, affecting firm energy generation and grid stability (Asian Development Bank, 2019). Meanwhile, the environmental and social impacts of hydropower development increase attention to where and how future projects should be developed. This makes cascaded hydropower systems on tributary rivers a particularly relevant context for assessing whether floating photovoltaics can improve reservoir-scale and inter-plant water–energy management (Mekong River Commission, 2022).

This study responds to that gap through the Nam Kong 2 (NK2)–Nam Kong 3 (NK3) cascade in southern Laos (see Figure 1). The two plants are approximately 13 km apart on the same river system, and therefore provide a practical case for examining both plant-level and cascade-level FPV–hydropower coordination. Rather than treating FPV integration as a stand-alone reservoir problem, the study evaluates how coordinated FPV deployment affects export adequacy, hydropower displacement, water saving and techno-economic performance across the coupled cascade. In this way, the research seeks to generate context-specific evidence for more effective water–energy management in Lao hydropower systems, and to extend FPV–hydropower research beyond the single-reservoir paradigm.

(a) Regional location of the NK2–NK3 cascade (b) Local view of the NK2–NK3 cascade

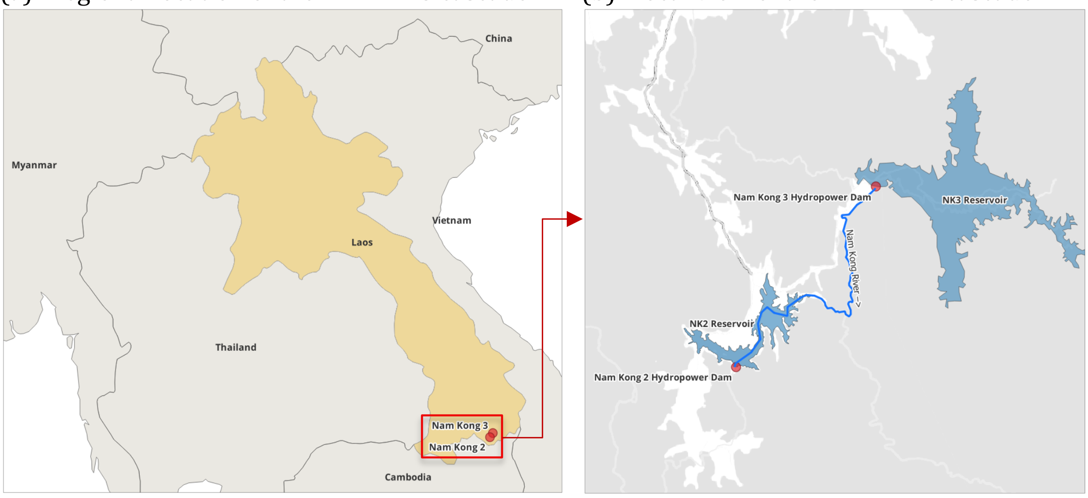

Figure 1. Location of the Nam Kong 2–Nam Kong 3 cascade study area

1.1. Objective of the paper

The objective of this paper is to assess the techno-economic performance of coordinated FPV integration in the NK2–NK3 cascade in southern Laos, with specific emphasis on how FPV placement and coordinated operation affect export adequacy, hydropower substitution, cluster water saving and the practical suitability of alternative deployment layouts. A secondary objective is to determine whether upstream-dominant, downstream-only, or asymmetric layouts offer greater benefits for water–energy management in the cascade.

2. Literature review

This section reviews the literature relevant to coordinated FPV–hydropower integration in cascaded reservoirs. It focuses on previous studies on FPV–hydropower hybridisation, coordinated operation, cascade hydropower management and techno-economic evaluation. The purpose of this review is to identify the main knowledge gap and to position the present study in relation to the paper's objective.

2.1. FPV–hydropower integration and techno-economics

Floating photovoltaic (FPV) integration with hydropower reservoirs offers several well-known benefits. Firstly, FPV systems are land-efficient because they use existing reservoir surfaces rather than competing with agriculture, settlements or other land uses. This makes FPV systems particularly attractive in regions where hydropower infrastructure already exists and suitable land for large solar deployment is limited (Kakoulaki et al., 2023; Solomin et al., 2021). Secondly, FPV systems can benefit from module cooling above water surfaces, which helps lower operating temperatures and improve module efficiency compared to ground-based systems (Agrawal et al., 2025; Farrar et al., 2022; Hao et al., 2025; Kassem et al., 2024). Therefore, this effect of water-based cooling reinforces the importance of reservoir conditions in FPV performance (Chen et al., 2024; Gorjian et al., 2021; Solomin et al., 2021). Thirdly, FPV can reduce reservoir evaporation by shading part of the water surface. Evaporation reduction is one of the most frequently reported benefits in regards to FPV deployment (Hao et al., 2025; Jin et al., 2023; Nasir et al., 2023; Peters et al., 2024). Similarly, the technology may also suppress algae growth and improve water quality, which are important environmental advantages (Baradei and Sadeq, 2020). Most importantly, FPV offers complementary generation with hydropower. Daytime solar output can reduce the need for immediate hydropower dispatch, allowing water to be conserved for later use and potentially reducing seasonal generation volatility (Stunjek and Krajačić, 2025). All the literature agrees that FPV–hydropower integration resulted in higher total energy output, lower power volatility, and improved utilisation of existing infrastructure (Kimura et al., 2024; Nahar et al., 2024). Lao case studies at Nam Mang 3, Nam Ngum 1, Huay Lamphan Gnai, and Nam Theun 2 further indicate that even modest FPV coverage can increase annual output and improve seasonal complementarity (Kimura et al., 2024; Nhiavue et al., 2022; Sisomboune et al., 2024a). Overall, these benefits show that FPV–hydropower hybridisation is a promising solution to improving both renewable electricity production and reservoir-based water–energy management.

The techno-economic evidence for FPV–hydropower integration remains promising but still fragmented. Economic assessments are often inconsistent across studies. Many papers refer to levelised cost of electricity (LCOE), but only a minority report full numerical estimates or disclose comparable assumptions. Several studies reported that LCOE values generally fall within a broad range of about 5–14.2 US cents per kWh, while only a few cases provide internal rate of return (IRR) or net present value (NPV) results (Brent et al., 2024; Kimura et al., 2024; Nguyen et al., 2023; Shah Irshad et al., 2024; Sisomboune et al., 2024b). Sensitivity analyses most often focus on capital expenditure (CAPEX) and tariff assumptions, but other parameters such as operation and maintenance cost, weighted average cost of capital, system lifetime and performance ratio are less transparently reported, which limits cross-study comparability and weaken investment confidence. In the Lao context, studies show that economic viability is highly sensitive to CAPEX, system efficiency, wholesale electricity price and broader financial conditions, indicating that technical promise alone does not guarantee bankability (Kimura et al., 2024; Sisomboune et al., 2024b).

Another related issue is the strong uncertainty surrounding FPV feasibility and appropriate deployment scale. Most FPV–hydropower studies begin with conservative coverage ratios of around 5–10% of reservoir area and FPV-to-hydropower capacity ratios of roughly 0.5–1.5 (Nguyen et al., 2023; Sisomboune et al., 2024b). However, the reported feasible ranges vary widely across sites because ecological, hydrological, technical and economic conditions differ markedly. Some studies suggest that 10–25% surface coverage can substantially increase power output while others recommend even higher ranges of 40–60% when environmental and operational trade-offs are considered (Haas et al., 2020; Jin et al., 2023; Kimura et al., 2024). In Laos, however, existing case studies remain much smaller, typically examining only about 1–2.24% reservoir coverage, and explicitly note that their findings are site-specific rather than generally transferable (Kimura et al., 2024; Sisomboune et al., 2024a). A study at Nam Mang 3 in Laos suggests that an FPV capacity of around 100–150% of hydropower capacity may reduce curtailment, but the real-world applicability of such ratios remains uncertain because empirical validation is limited and outcomes depend strongly on local grid capacity, demand conditions and pricing arrangements (Kimura et al., 2024). Taken together, the literature suggests that FPV feasibility cannot be inferred from generic benchmarks alone and instead requires case-specific assessment of both technical performance and economic viability.

2.2. Cascade hydropower coordination and inter-plant water–energy management

Cascade hydropower is already a mature research field in terms of coordinated scheduling, hydraulic coupling and multi-source system operation. Recent studies show that cascade stations are not operated as isolated plants, but as interconnected systems in which reservoir levels, releases, generation intervals and transmission requirements must be managed jointly. In this context, hydropower acts as a key regulating resource for accommodating variable renewable energy, especially where wind and photovoltaic generation increase system uncertainty and place additional pressure on operational flexibility. As a result, cascade scheduling research increasingly focuses on multi-reservoir coordination, stochastic inflow treatment, robust optimisation and the definition of feasible generation ranges under complex operating constraints (Giuliani et al., 2021; Kangrang et al., 2023; Li et al., 2025; Soomro et al., 2023; Wang et al., 2023; Zhou et al., 2021).

A central feature of cascade systems is hydraulic coupling between upstream and downstream plants. Upstream releases affect downstream inflow, reservoir level, turbine discharge, spill behaviour and the timing of power production, which means that operating decisions at one plant propagate through the cascade rather than remaining local. For example, Liu et al. (2025) model cascade serial diversion hydropower-wind-solar systems by explicitly enforcing upstream–downstream flow matching and complex short-term operational constraints, while Rot Weiss et al. (2025) show that even real-time cascade dispatch must account for nonlinear head–flow relationships, reservoir limits and inter-plant water transfers. These studies demonstrate that downstream adequacy is strongly influenced by upstream operating decisions. As a result, cascade management should evaluate water balance, release timing and spill at the system level across linked reservoirs rather than treating each reservoir in isolation.

This hydraulic interdependence becomes even more important under multi-source coordination. Wang et al. (2025) show that under high penetration of variable renewable energy, cascade hydropower scheduling must explicitly balance water spillage and power curtailment, with hydropower plants of different regulating capacities playing different roles in seasonal compensation. Similarly, Li et al. (2025) argue that large cascade hydropower systems are valuable for balancing multi-source power systems but their flexibility is limited by upstream–downstream hydraulic interactions, uncertain reservoir conditions, and the need to set feasible generation ranges for day-ahead operation. In parallel, recent work on cascade maintenance and transmission coordination indicates that generation dispatch in large cascade systems is also influenced by load conditions, transmission capacity, maintenance timing and broad system-level obligations. This reinforces the view that cascade hydropower is fundamentally a system–coordination problem rather than a collection of independent plants (Li et al., 2025).

2.3. Research gap

Despite growing research on FPV–hydropower hybridisation and the maturity of cascade hydropower scheduling studies, their integration remains limited. Most FPV–hydropower studies still assess individual reservoirs while cascade hydropower studies rarely examine how FPV placement and solar-driven hydropower substitution affect inter-plant operation. As a result, there is much needed guidance on how coordinated FPV deployment in cascaded reservoirs influences export adequacy, downstream support, cluster water saving and the relative suitability of upstream-dominant, downstream-only or asymmetric layouts (Giuliani et al., 2021; Kangrang et al., 2023; Li et al., 2025; Soomro et al., 2023; Zhou et al., 2021). This study addresses this gap through the NK2–NK3 cascade in Laos by evaluating coordinated FPV placement at both plant and cascade levels.

3. Research methods

3.1. Case study description

The case study considers the NK2 and NK3 hydropower plants in Attapeu Province, southern Laos. The two plants are located on the same river system and form a cascaded hydropower pair separated by approximately 13 km. Downstream NK2 has an installed hydropower capacity of 66 MW and a reservoir storage of about 71.4 million m^3, while upstream NK3 has an installed hydropower capacity of 54 MW and a reservoir storage of about 471 million m^3. Both plants are connected to the transmission network through 115 kV infrastructure, and the cascade is linked to the Bo Y interconnection through a shared export corridor (see Figure 2). This hydraulic linkage makes the pair suitable for analysing both stand-alone and coordinated FPV–hydropower operations.

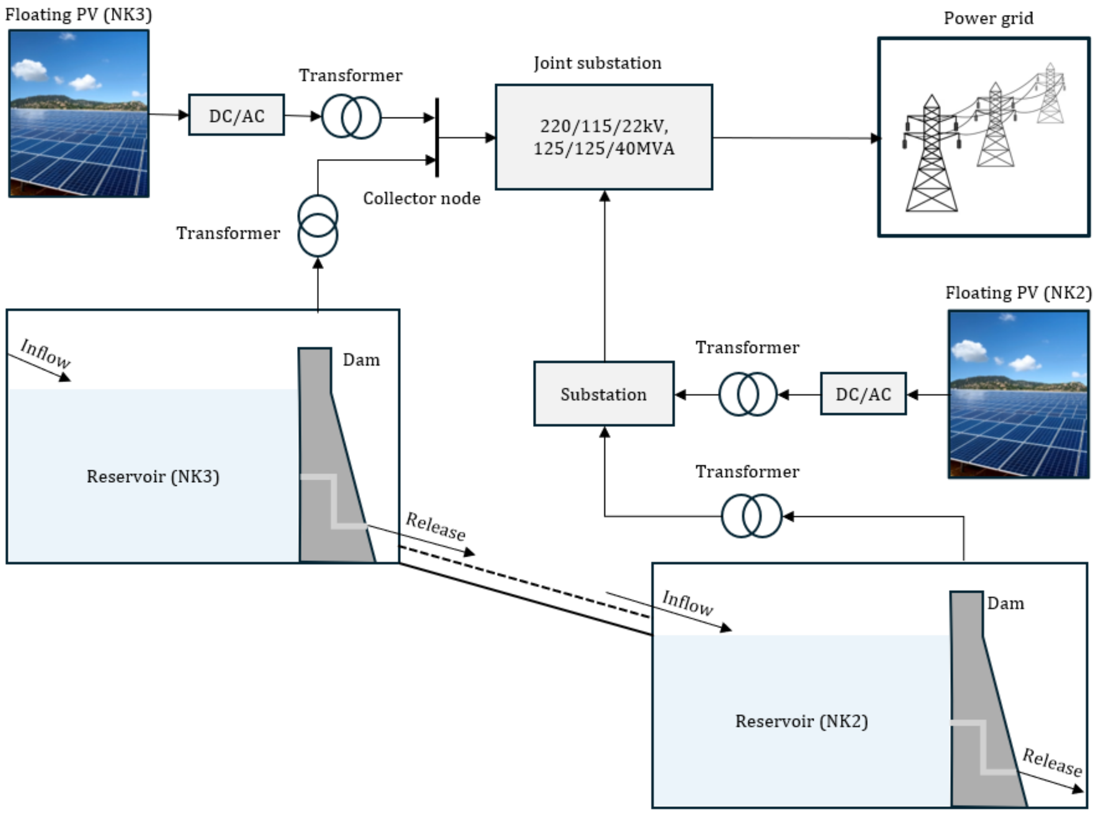

Figure 2. Case study schematic of the NK2–NK3 cascade
(Source: Derived from Power-China Chengdu Engineering Corporation Limited, 2021)

3.2. Modelling framework

The modelling framework is summarised in Figure 3. Hourly FPV output was simulated in PVsyst for each design scenario and then integrated with plant hydro and reservoir data in an Excel-based coordinated dispatch model. The framework combines hourly energy allocation with daily reservoir storage updates, including cascade routing from NK3 to NK2 to evaluate how FPV changes hydropower use, storage, spill and export adequacy relative to the observed baseline delivery behaviour of the NK2–NK3 cluster.

Hourly FPV generation from PVsyst was combined with plant hydro and reservoir data in an Excel-based coordinated dispatch and daily storage model. The framework links plant-level solar dispatch, cluster-level export constraints, cascade routing, reservoir updates and performance assessment across 21 FPV design scenarios (see the supplementary material).

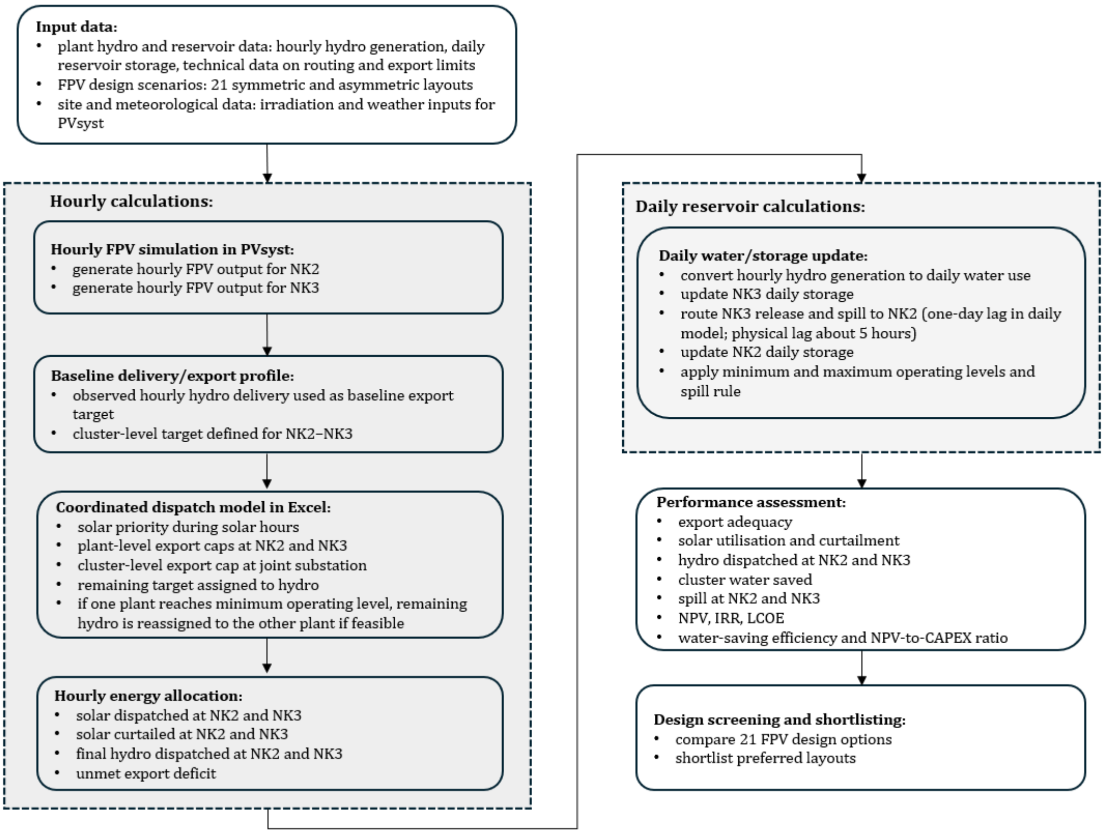

Figure 3. Modelling framework to evaluate coordinated FPV–hydropower integration in the NK2–NK3 cascade

3.3. Modelling cascade coupling between NK2 and NK3

The coupled model treated the observed hydro generation profiles as the baseline delivery behaviour and then tested how FPV changes hydro dispatch, storage and spill under explicit control rules. Because NK2 and NK3 feed the same export grid at the joint substation, the relevant research question was not whether each plant could maintain its former output independently but whether the NK2–NK3 cluster could maintain its target export while respecting plant limits, reservoir dynamics and cascade routing.

Available solar generation was calculated separately for NK2 and NK3. Solar dispatch was then determined at the plant level, subject to local export limit of each plant. Thus, the solar used at NK2 and NK3 in hour h was equal to the minimum of available solar output and the respective plant-level export cap. Total cluster solar dispatch was the sum of solar used at the two plants. The remaining export requirement was then assigned to hydropower. Detail of the coupling model is as follows:

Available solar in hour h at each plant:

For NK2: $P_{NK2,h}^{PV,avail}$

For NK3: $P_{NK3,h}^{PV,avail}$

Solar was dispatched first at each plant, subject to the local plant export limit.

If the local export caps are C_{NK2} and C_{NK3}, then:

$$P_{NK2,h}^{PV,use} = \min(P_{NK2,h}^{PV,avail}, C_{NK2}) \quad (1)$$

$$P_{NK3,h}^{PV,use} = \min(P_{NK3,h}^{PV,avail}, C_{NK3}) \quad (2)$$

This means each plant's solar is first limited by its own local delivery capability, not by the cluster constraint.

Total solar used by the cluster:

$$P_{h}^{PV,use} = P_{NK2,h}^{PV,use} + P_{NK3,h}^{PV,use} \quad (3)$$

The target export in hour h was defined as T_h. The cluster export available to the grid was constrained by the joint export cap C^{cl}:

$$T_h^* = \min(T_h, C^{cl}) \quad (4)$$

Thus, the remaining hydro requirement is:

$$H_h^{req} = \max(0, T_h^* - P_h^{PV,use}) \quad (5)$$

This remaining requirement was allocated between NK2 and NK3 subject to plant-level capacity, storage status and local hydro-plus-FPV headroom. If one reservoir reached its minimum operating level, that plant's hydro generation was set to zero and the remaining requirement was reassigned to the other plant if feasible. In this way, the coupling logic represented the practical situation in which one plant supports delivery while the other recovers storage.

Daily water use was linked to hourly hydro generation through plant-specific energy-to-water factors. Let α_{NK2} = 4.11 m^3 per kWh and α_{NK3} = 4.05 m^3 per kWh (unpublished plant data, 2024). The daily turbine water use for plant i on day d after coordination was calculated as:

$$G_{i,d}^{after} = \alpha_i \sum_{h \in d} H_{i,h}^{after} \quad (6)$$

where $H_{i,h}^{after}$ is the hourly hydro generation assigned to plant i after coordination.

To preserve consistency with the plant baseline data, the daily reservoir calculation used as baseline non-generation balance term derived from the observed storage and hydro series. For each plant:

$$B_{i,d}^{base} = V_{i,d}^{base} - V_{i,d-1}^{base} + G_{i,d}^{base} \quad (7)$$

where:

- $V_{i,d}^{base}$ is the observed daily end-of-day storage at plant i on day d.
- $V_{i,d-1}^{base}$ is the observed daily end-of-day storage at plant i on day $d-1$.
- $G_{i,d}^{base}$ is the baseline daily hydro water use at plant i on day d.

This term captures the unchanged local inflow and outflow components other than turbine water use.

For NK3, the raw daily storage after coordinated dispatch was:

$$V_{NK3,d}^{raw} = V_{NK3,d-1}^{after} + B_{NK3,d}^{base} - G_{NK3,d}^{after} \tag{8}$$

where:

- $V_{NK3,d-1}^{after}$ is daily storage of NK3 after coordination on day $d-1$.
- $B_{NK3,d}^{base}$ is daily baseline non-generation balance for NK3 on day d.
- $G_{NK3,d}^{after}$ is daily turbine water use for NK3 after coordination on day d.

For NK2, inflow was updated from upstream NK3 release and spill. The change in inflow to NK2 caused by the change in upstream NK3 operation was:

$$\Delta I_{NK2,d} = (G_{NK3,d}^{after} + S_{NK3,d}^{after}) - (G_{NK3,d}^{base} + S_{NK3,d}^{base}) \tag{9}$$

where:

- $G_{NK3,d}^{after}$ is daily turbine release from NK3 after coordination on day d.
- $S_{NK3,d}^{after}$ is daily spill from NK3 after coordination on day d.
- $G_{NK3,d}^{base}$ is baseline daily turbine release from NK3 on day d.
- $S_{NK3,d}^{base}$ is baseline daily spill from NK3 on day d.

The resulting NK2 raw storage was:

$$V_{NK2,d}^{raw} = V_{NK2,d-1}^{after} + B_{NK2,d}^{base} + \Delta I_{NK2,d} - G_{NK2,d}^{after} \tag{10}$$

where:

- $V_{NK2,d-1}^{after}$ is daily storage of NK2 after coordination on day $d-1$.
- $B_{NK2,d}^{base}$ is daily baseline non-generation balance for NK2 on day d.
- $\Delta I_{NK2,d}$ is the change in inflow to NK2 caused by the change in upstream NK3 operation on day d.
- $G_{NK2,d}^{after}$ is daily turbine water use at NK2 after coordination on day d.

Therefore, the model assumed that all other local inflows and outflows at both plants remained unchanged from the observed plant data while the upstream contribution from NK3 was updated according to the coordinated dispatch. The hydraulic connection from NK3 to NK2 was represented as one-day routing lag in the daily reservoir model. This assumption was adopted because the physical travel time between the two plants is approximately 5 hours over about 13 km. However, the reservoir balance was implemented at a daily time step. This was the main mechanism through which cascade interactions were incorporated into the reservoir model.

3.4. Constraints and dispatch assumptions

The dispatch model adopted a solar-priority rule. During solar hours, PV was accepted first and hydropower was reduced by the same amount wherever technically feasible. During non-solar hours, hydropower supplied the remaining demand subject to storage and release constraints. This rule was chosen because the main scenario of interest was not exporting maximisation beyond the current delivery profile, but water saving while maintaining existing delivery.

The model used both plant-level and cluster-level constraints. In the conservative base case, the combined hydro-plus-FPV output at each plant was limited by the local plant export capacity, taken as 66 MW for NK2 and 54 MW for NK3, while the cluster was additionally constrained by a 120 MW joint export cap associated with the Bo Y interconnection. In practical terms, the cluster export had to satisfy:

$$P_{NK2,h}^{out} + P_{NK3,h}^{out} \leq 120 \text{ MW} \tag{11}$$

and, conservatively:

$$P_{NK2,h}^{hydro} + P_{NK2,h}^{PV} \leq 66 \text{ MW} \tag{12}$$

$$P_{NK3,h}^{hydro} + P_{NK3,h}^{PV} \leq 54 \text{ MW} \tag{13}$$

Minimum and maximum operating reservoir volumes were imposed at both plants. When the raw daily storage exceeded the maximum operating level, spill was generated as:

$$S_{i,d}^{after} = \max(0, V_{i,d}^{raw} - V_i^{max}) \tag{14}$$

where:

- $S_{i,d}^{after}$ is water spill at plant i on day d after coordination.
- $V_{i,d}^{raw}$ is raw storage of plant i on day d.
- V_i^{max} is maximum operating reservoir volume of plant i.

Final daily storage was then limited to the operating range:

$$V_{i,d}^{after} = \min(V_i^{max}, \max(V_i^{min}, V_{i,d}^{raw})) \tag{15}$$

where:

- V_i^{max} is the maximum operating storage of plant i.
- V_i^{min} is the minimum operating storage of plant i.
- $V_{i,d}^{raw}$ is raw storage of plant i on day d.

Under this hard-cutoff rule, if the storage falls to V_i^{min}, hydropower can no longer be supplied until storage is recovered. In the coupled model, the remaining hydro requirement was then assigned to the other plant if that plant still had hydropower headroom. This rule was central to the cascade behaviour because it allowed one reservoir to refill while the other provided support to maintain cluster delivery.

A total of 21 FPV designs were tested in the coordinated model (see the supplementary material). These include symmetric and asymmetric layouts, south-facing and east-west layouts, NK2-only cases, NK3-only cases and reduced-NK3 cases. The design matrix was intentionally used as a sensitivity test on FPV size and placement to determine whether downstream-only, upstream-dominant, or asymmetric layouts gave better results for water saving, solar utilisation, export adequacy and techno-economic performance.

3.5. Performance indicators

Energy, water and economic indicators were utilised. The primary hourly energy indicators were solar dispatched, solar curtailed, hydro dispatched at NK2, hydro dispatched at NK3 and unmet export deficit. Export adequacy was tracked by comparing actual cluster export with the target export profile at the joint station. At the daily level, the model reported plant storage trajectories, cluster water saved, spill at NK2 and NK3 and water release from NK3. These variables reveal how solar substitution changes both local and inter-plant water behaviour.

The economic performance was evaluated using all-in CAPEX and OPEX assumptions from a feasibility material (Power-China Chengdu Engineering Corporation Limited, 2021) and the economic evaluation outputs generated by PVsyst. The main economic indicators were net present value (NPV), internal rate of return (IRR), and levelised cost of electricity (LCOE), as reported by the PVsyst economic module. In addition, two derived indicators were calculated to support comparison across design options.

First, a water-saving efficiency indicator was used to compare hydrological benefit per unit of investment:

$$WSE = \frac{Cluster\ water\ saved\ (m^3)}{Total\ CAPEX\ (million\ USD)} \tag{16}$$

Second, an NPV-to-CAPEX ratio was used to compare economic return relative to initial investment:

$$NPV-to-CAPEX = \frac{Total\ NPV\ (USD)}{Total\ CAPEX\ (USD)} \tag{17}$$

where:
- Total NPV means the combination of NPV of FPV systems at NK2 and NK3.
- Total CAPEX means the combination of CAPEX of FPV systems at NK2 and NK3.

3.6. Limitations

The model was designed to be transparent and operationally interpretable rather than fully optimised. Therefore, several limitations apply. Firstly, stochastic inflow uncertainty was not modelled. Although the study used recent data from 2024, this dataset may not adequately represent the annual variability in hydrological conditions. Secondly, the hydraulic routing lag from NK3 to NK2 was represented in simplified fixed-delay form rather than by dynamic channel routing. Thirdly, turbine efficiency was treated as a constant through the plant-specific water-to-energy conversion factors, even though efficiency varies with head and loading in practice (Rot Weiss et al., 2025). Fourthly, dynamic transmission stability, ancillary services, and internal network losses were not modelled. Fifthly, evaporation reduction from FPV coverage was excluded from the operational model, so the water-saving results represent hydropower-substitution water saving rather than total physical water conservation. Finally, some local transformers and export-cap ratings remain uncertain; therefore, the 66 MW, 54 MW, and 120 MW caps should be interpreted as conservative operational assumptions unless future project verification provides better values. These limitations are stated explicitly so that results are interpreted as scenario-based operational evidence under simplified but transparent assumptions, rather than as a full real-time plant-control simulation.

4. Results

This section presents the results of the coordinated FPV–hydropower model for the NK2–NK3 cascade. Firstly, it establishes the baseline cluster behaviour used as the reference export profile. Secondly, it examines how coordinated solar substitution changes hydropower use, storage, spill and export adequacy. Thirdly, the section compares the 21 FPV layouts and identifies the technically and economically preferred design options.

4.1. Baseline operational behaviour of the NK2–NK3 cascade

The observed hydro generation profile of the NK2–NK3 cluster was used as the baseline delivery behaviour against which FPV scenarios were assessed. The baseline hydro and reservoir data provide both the hourly export reference and the daily storage reference for the coupled simulations. Under baseline conditions, the cascade already exhibits clear upstream–downstream dependence (see **Figure 4**). NK3 affects NK2 not only through power delivery at the shared export point, but also through its control of downstream release support. This means that the performance of the cluster cannot be assessed from plant-level generation alone. Instead, baseline export adequacy, reservoir behaviour, and release patterns together define the reference against which coordinated FPV deployment must be judged.

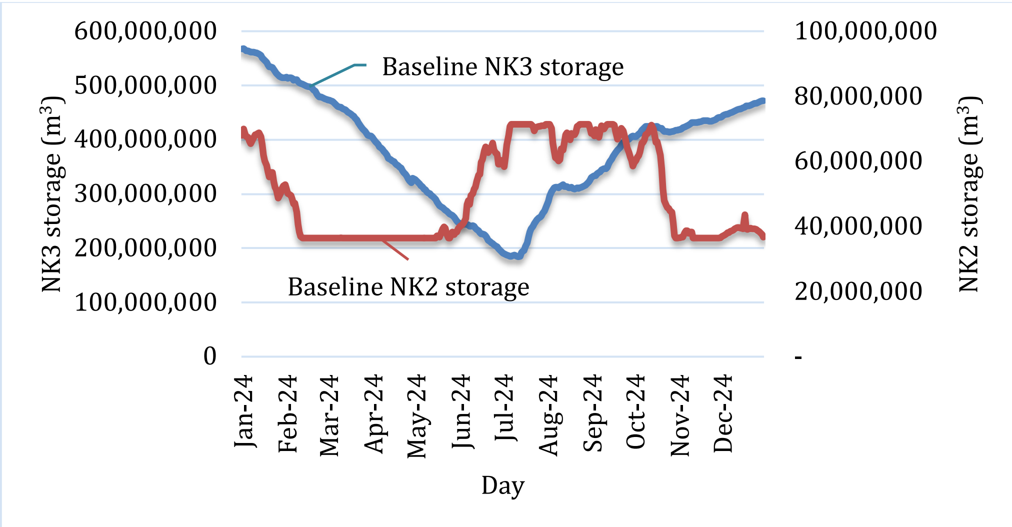

Figure 4. Baseline daily storage trajectories of the NK3 and NK2 reservoirs in 2024

4.2. Effects of coordinated solar substitution on hydropower use and storage

Introducing FPV into the cascade changed hydropower operation through the solar-priority dispatch rule. During solar hours, accepted photovoltaics reduced immediate hydropower dispatch, thereby conserving water that could be retained in storage or used later when solar output was unavailable. At the plant level, this created the expected substitution effect: solar generation displaced part of hydro generation and reduced daytime turbine water use. However, in the cascade setting the effect is not purely local. Reduced hydropower dispatch at the upstream plant also changed downstream inflow support, which in turn affected NK2 storage, hydropower feasibility, and the ability of the cluster to maintain the target export. Figure 5 summarises this system-level trade-off by comparing unmet export deficit against cluster water saving across all 21 FPV layouts.

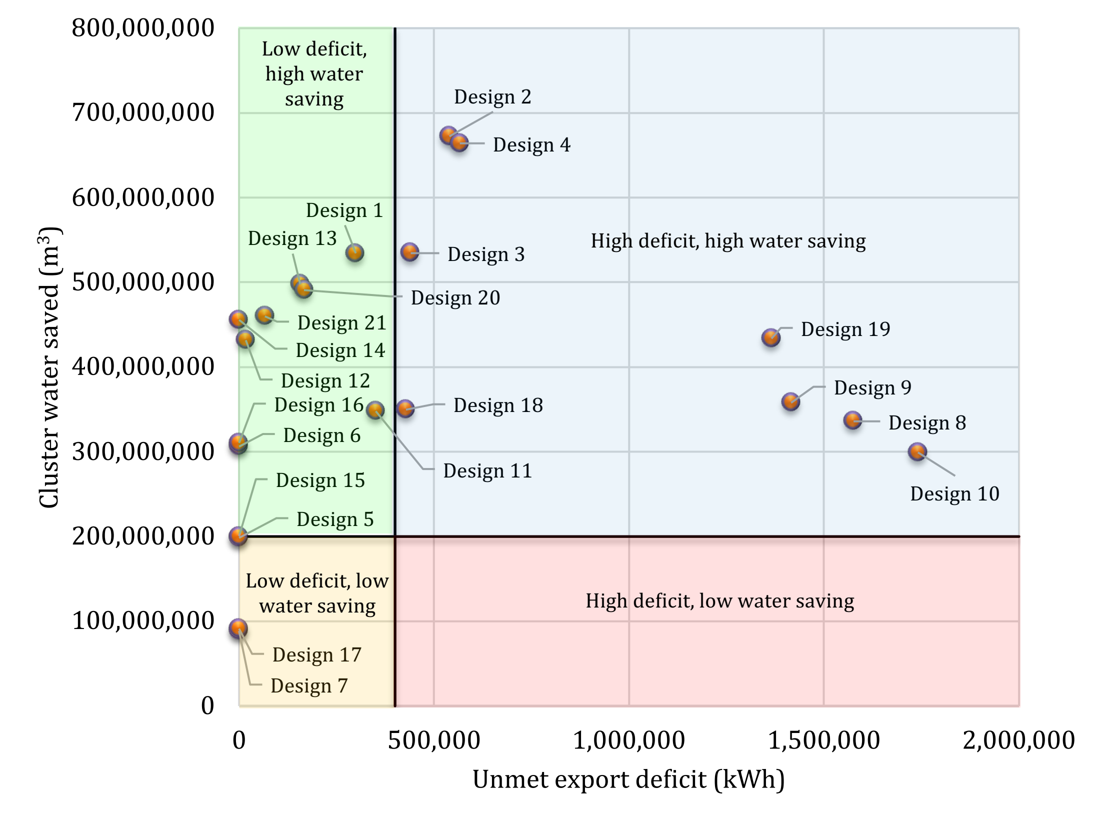

Figure 5. Trade-off between export adequacy and cluster water saving for all 21 FPV designs

This result shows that plant-level water saving is not sufficient as the main evaluation metric in a cascaded system. A layout can save water at one reservoir while simultaneously weakening downstream support and worsening export adequacy at the cluster level. For this reason, the coupled simulations were evaluated using cluster-level indicators such as unmet export deficit, total hydro dispatch, cluster water saved, and spill at both reservoirs rather than relying only on local reservoir outcomes.

4.3. Comparison of FPV layouts

A total of 21 FPV layouts were tested, including symmetric, asymmetric, NK2-only, NK3-only, and reduced-NK3 cases. The initial symmetric cases showed that large upstream FPV deployment at NK3 caused substantial curtailment and altered cascade release behaviour in a way that weakened downstream support to NK2. In other words, increasing FPV capacity at the upstream reservoir did not necessarily improve cluster performance. In several cases, it increased solar curtailment and reduced the ability of the cluster to maintain the target export.

By contrast, downstream-only and downstream-dominant layouts performed more robustly. These layouts used solar more effectively, preserved export adequacy more consistently, and still deliver meaningful water savings, as indicated by the shortlisted designs in Figure 6a and Figure 6b and their corresponding configurations in Table 1a. Therefore, the results indicate that FPV placement within the cascade is more important than simply increasing total installed FPV capacity. This is consistent with the coordinated modelling logic, under which upstream solar not only substitutes upstream hydro but also affects downstream inflow, release support and storage recovery.

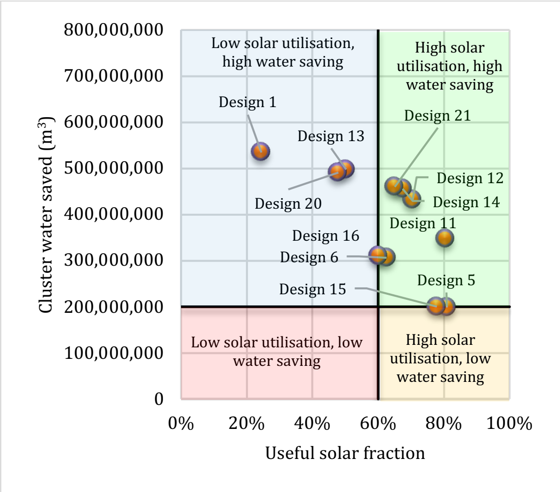

Figure 6a. Water saving versus solar utilisation among shortlisted designs in green zone of Figure 5

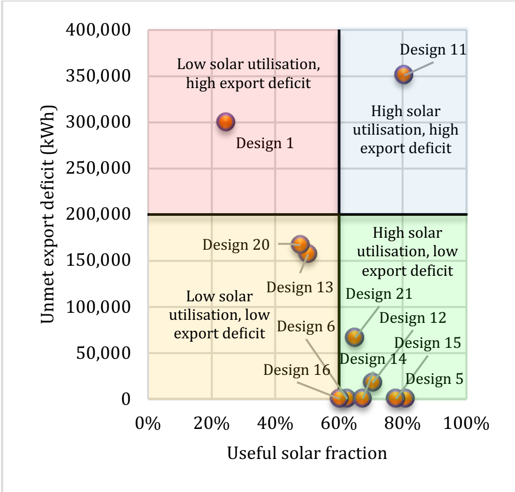

Figure 6b. Export adequacy versus solar utilisation among shortlisted designs in green zone of Figure 5

The technical screening process used export adequacy, water saving, and solar utilisation to identify preferred designs, with the shortlisted configurations summarised in Table 1a and Table 1b. The result shows that the preferred set was not dominated by NK3-heavy layouts but instead by layouts with no FPV at NK3 or only modest upstream FPV, combined with moderate deployment at NK2. The final shortlist, therefore, focused on four practical candidates: FPV NK3 = 0% with FPV NK2 = 5% reservoir coverage, FPV NK3 = 0% with FPV NK2 = 10% reservoir coverage, FPV NK3 = 1% with FPV NK2 = 5% reservoir coverage, and FPV NK3 = 0.5% with FPV NK2 = 10% reservoir coverage. These layouts were retained for the final techno-economic comparison.

Table 1a. Shortlisted FPV designs and key technical indicators

Design	NK3 layout	NK2 layout	Useful solar fraction (%)	Unmet export deficit (MWh)	Cluster water saved in 2024 (Mm³)
5	None	E–W, 5%	81	0.10	198.5
6	None	E–W, 10%	63	0.19	306.2
12	E–W, 1%	E–W, 5%	71	17.36	431.8
14	E–W, 0.5%	E–W, 10%	67	0.27	455.7
15	None	S, 5%	78	0.10	200.4
16	None	S, 10%	60	0.20	310.6
21	S, 0.5%	S, 10%	65	66.28	459.9

Note: All FPV configurations use a 10° tilt. The percentage values in the NK3 and NK2 layout columns indicate the proportion of the corresponding reservoir surface area covered by FPV. None = no FPV deployment at the corresponding reservoir; MWh =

megawatt-hour; Mm^3 = million cubic metres; E–W = east–west orientation; S = south-facing as illustrated in Figure 7.

Table 1b. Shortlisted FPV designs and key economic indicators

Design	Total CAPEX (MUSD)	Water-saving efficiency (Mm^3/MUSD)	NPV-to-CAPEX ratio (%)
5	31.94	6.21	3.88
6	63.88	4.79	3.61
12	80.47	5.37	3.73
14	88.14	5.17	4.21
15	31.94	6.27	3.88
16	63.88	4.86	3.61
21	88.14	5.22	4.21

Note: Mm^3 = million cubic metres; MUSD = million USD.

(a) South-facing FPV layout with 10° tilt (b) East–West FPV layout with 10° tilt

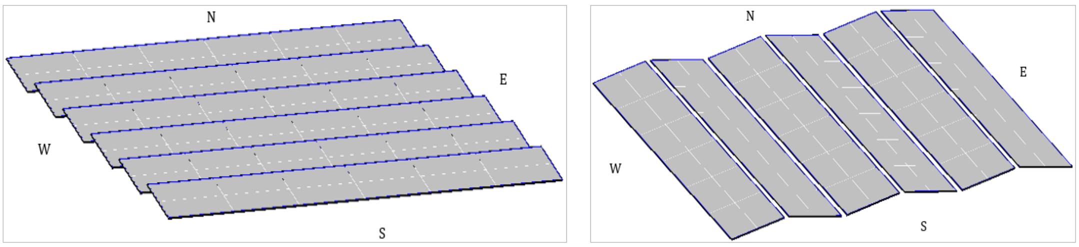

Figure 7. Representative FPV layout configurations used in the design screening

4.4. Techno-economic screening of shortlisted layouts

The techno-economic results further refined the technical shortlist. Economic indicators were obtained from the PVsyst economic evaluation and complemented by two derived indicators: water-saving efficiency and the NPV-to-CAPEX ratio. These additional indicators were useful because absolute water saving and economic attractiveness did not always move in the same direction. Some layouts with higher total water saving also required substantial higher investment, reducing their water-saving benefit per unit of CAPEX, as illustrated in Figure 8.

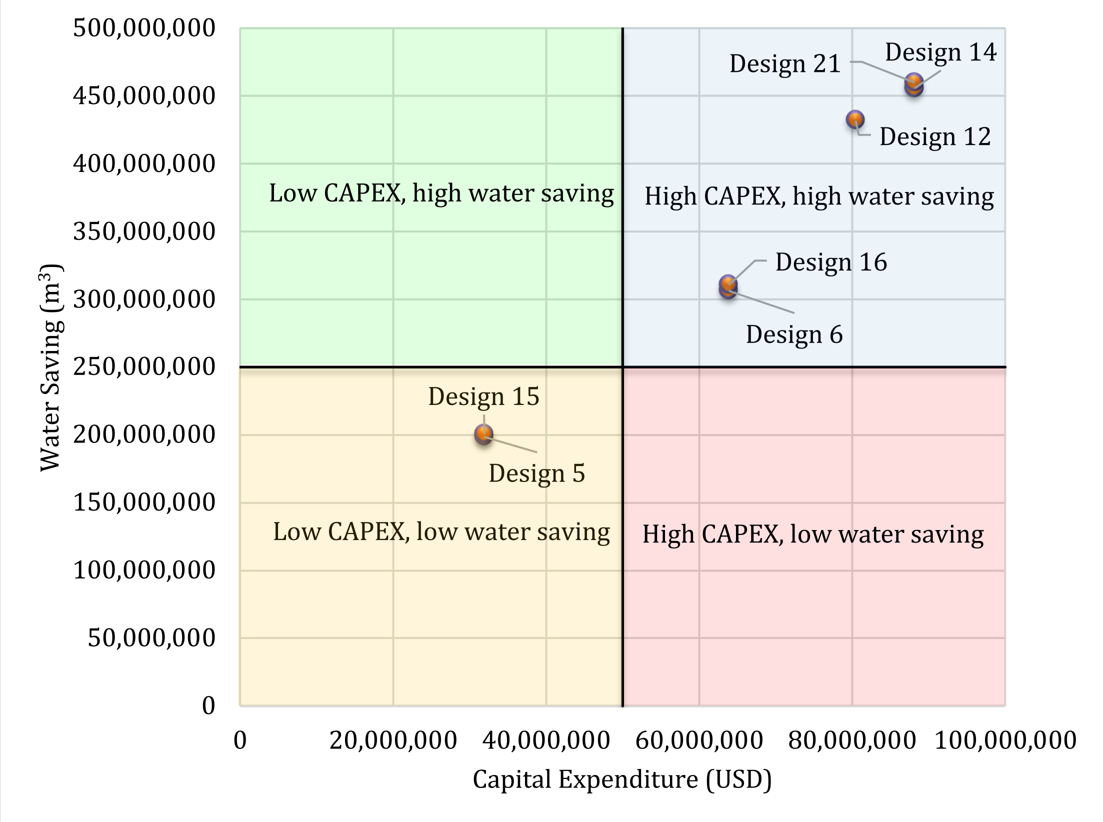

Figure 8. Water saving versus CAPEX among shortlisted FPV designs in the green zones of Figure 6a and Figure 6b

Therefore, the shortlisted layouts did not point to a single universally optimal design. Instead, they revealed two practical categories. The first category consists of water-priority designs, which maximise total cluster water saving but require larger investment. The second category consists of cost-efficient designs, which deliver lower absolute water saving but perform better in terms of water saved per unit CAPEX or economic return relative to capital cost. This distinction is important because the objective of this study is not to identify one final design for universal adoption but to show how coordinated FPV placement changes water–energy management options in the NK2–NK3 cascade.

4.5. Main result

Overall, the results show that coordinated FPV integration does not improve all layouts equally. Upstream-heavy deployment at NK3 tends to underperform because it weakens downstream support and increases curtailment, whereas downstream-only or downstream-dominant layouts preserve export adequacy more effectively while still delivering meaningful water saving. Therefore, the results suggest that in cascaded systems, FPV should be evaluated primarily as a cluster-level water–energy management option rather than as an isolated plant-level solar addition. This finding provides the basis for the broader interpretation developed in section 5.

5. Discussion

The results show that coordinated FPV integration in a cascade cannot be interpreted in the same way as FPV integration at a single reservoir. In stand-alone FPV–hydropower studies, solar substitution is usually treated as a local benefit because daytime solar reduces immediate hydropower use and conserves water at the same reservoir. However, in the NK2–NK3 cascade, the consequences of solar substitution extend beyond the plant where the solar generation is installed. Upstream solar does not only reduce upstream hydropower dispatch; it can also reduce downstream inflow support, alter release timing, and change the ability of the cascade to maintain the target export profile. This means that the plant-level water saving is not sufficient as the main performance metric in a cascaded system. Instead, FPV must be evaluated against cluster-level outcomes, particularly export adequacy, inter-plant support, spill, and total cluster water saving.

5.1. What the cascade changes

The cascade changes the meaning of solar substitution. In a single-reservoir setting, conserved water remains available for later use at the same plant. In a cascade, conserved water at the upstream plant also affects the downstream plant through routing, release support, and storage recovery. As a result, the same amount of solar generation can produce different system outcomes depending on where it is installed (Liu et al., 2025). The coordinated model shows that this spatial effect is fundamental: the value of FPV is determined not only by how much hydropower it displaces locally, but also by how that displacement changes downstream adequacy and cluster delivery. The main implication is that plant-level optimisation is insufficient for cascaded systems because it can overstate the benefit of upstream solar if downstream impacts are ignored.

This also explains why the cluster-level framing adopted in this study is important. Because NK2 and NK3 feed a common export point, the relevant operational question is not whether each plant preserves its previous generation independently, but whether the cascade can continue to satisfy the observed delivery behaviour while benefiting from solar substitution (Li et al., 2025). This shift from plant-level to cluster-level assessment is one of the main methodological contributions of the study.

5.2. Why NK3-heavy layouts underperform

The underperformance of NK3-dominant layouts can be explained through the interaction between solar substitution and cascade support. When a large share of FPV is placed at NK3, daytime solar reduces NK3 hydropower dispatch. Although this option saves water locally, it also weakens the release support that NK3 provides to downstream system. In the coordinated simulations, that reduction in upstream support constrains NK2 inflow and limits the downstream plant's ability to maintain generation when required (Liu et al., 2025). At the same time, upstream-heavy solar increases the risk that available solar cannot be fully used within plant-level and cluster-level limits, which contributes to higher curtailment. As a result, a layout that appears attractive from the perspective of local water saving at NK3 can still underperform in terms of export adequacy and overall cascade behaviour (Rot Weiss et al., 2025).

This mechanism helps explain why downstream-only and downstream-dominant layouts performed better. Solar deployed at NK2 directly supports the downstream part of the cascade without weakening an upstream support function. Modest upstream FPV deployments can still be useful but only when they do not materially reduce the downstream release support required to stabilise cluster delivery. This is why the shortlisted layouts converged toward NK2-only or strongly NK2-dominant operations rather than large symmetric or upstream-dominant layouts.

5.3. Implications for Laos and similar systems

These findings matter beyond the NK2–NK3 case because they suggest that FPV placement in cascaded systems should be both grid-aware and cascade-aware. In practice, this means that the suitability of an FPV site cannot be judged from reservoir area, solar resource, or plant-level water saving alone. The operational role of the reservoir within the cascade must also be considered, especially whether it serves as an upstream support source for downstream generation or whether it lies close to the shared export point. In such systems, downstream reservoirs may be first-priority FPV sites because solar deployed there is less likely to weaken downstream adequacy. By contrast, upstream FPV may need to be kept modest unless support-release rules, additional grid headroom, or other coordination mechanisms are available.

For Laos, the study suggests that cascade-based FPV planning should move beyond generic reservoir coverage rules and instead evaluate placement in relations to coordinated dispatch, export constraints, and inter-plant routing effects. This is particularly relevant in hydropower-dependent systems where seasonal water variability already constrains dry-season delivery. Under such conditions, the purpose of FPV is not simply to add solar generation, but to improve the overall water–energy management of the cascade. Therefore, the shortlisted layouts in this study should not be interpreted as a single final answer, but as practical examples of how coordinated FPV deployment can be adapted to different priorities, including export adequacy, water saving and capital efficiency.

6. Conclusions

This paper assessed the techno-economic performance of coordinated FPV integration in the NK2–NK3 cascade in southern Laos, with emphasis on export adequacy, hydropower substitution, cluster water saving, and the suitability of alternative deployment layouts. The results show that coordinated FPV integration in a cascade cannot be evaluated in the same way as FPV integration at a stand-alone reservoir. In the NK2–NK3 case, upstream solar substitution did not only conserve water at NK3 but also altered downstream inflow support, release timing and the ability of the cascade to maintain its target export. As a result, plant-level water saving alone was not a sufficient basis for judging FPV performance in the coupled system.

The coordinated simulations further show that FPV placement within the cascade is more important than simply increasing total installed FPV capacity. Large upstream FPV deployment at NK3 tended to increase solar curtailment and weaken downstream support to NK2, leading to poorer export adequacy. By contrast, downstream-only and downstream-dominant layouts maintained export adequacy more effectively while still delivering meaningful cluster water savings. Therefore, the results suggest that, in cascaded systems, the operational role of each reservoir within the linked system must be considered when selecting FPV size and location.

The study also showed that higher total water saving did not necessarily correspond to higher water-saving efficiency or stronger value relative to investment. Some larger layouts delivered greater absolute hydrological benefit, but at substantially higher capital cost. Consequently, the preferred options are better interpreted as different management choices rather than a single optimal design, depending on whether the planning priority is export reliability, total water saving, or capital efficiency.

The main contribution of this study is that it connects two bodies of literature that are usually treated separately: FPV–hydropower integration, and cascade hydropower coordination. By combining hourly FPV generation, cluster-level dispatch, daily reservoir updating and cascade routing, the study provides a practical framework for examining coordinated FPV placement in linked reservoirs. The results demonstrate that the critical question is not only how much solar capacity should be installed, but where within the cascade it should be installed and how the resulting solar substitution changes downstream support. This makes FPV placement an operational question as much as a generation or economic question.

6.1. Recommendations

For practice and planning, FPV deployment in cascaded hydropower systems should be designed using a cascade-aware and grid-aware approach rather than plant-level screening alone. In systems like NK2–NK3, downstream reservoirs should be treated as first-priority FPV sites unless there is clear evidence that upstream deployment will not weaken downstream adequacy. Where upstream FPV is considered, it should remain limited unless support-release rules, verified transfer headroom, or other operational arrangements can preserve downstream performance.

For the NK2–NK3 cascade specifically, the shortlisted layouts suggest that practical deployment should focus only on downstream-only or strongly downstream-dominant configurations, with only modest upstream participation where justified. These options appear to provide the best balance between maintaining export adequacy, conserving water at the cluster level, and limiting excessive capital expenditure. However, the final choice should depend on whether the planning priority is export reliability, total water saving, or cost efficiency.

For future research, three extensions are recommended. Firstly, the model should be expanded to include multi-year hydrological variation and stochastic inflow uncertainty rather than relying on a single recent year of plant data. Secondly, plant-level and cluster-level export constraints should be refined using verified transformer and corridor ratings, including possible differentiation between local plant limits and shared interconnection limits. Thirdly, future work should examine whether more advanced coordination strategies including dynamic routing and alternative release-support rules, can improve the performance of upstream FPV without undermining downstream adequacy. These extensions would strengthen the transferability of the present findings to other cascaded hydropower systems in Laos and comparable hydropower-dependent regions.

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