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

Purpose and scope:
This supplementary material provides additional supporting information for the article. Its purpose is to document the analytical pathway used to move from initial FPV–hydropower scenario generation to the final coordinated cascade interpretation, and to present supporting tables and figures that are informative but not essential to the main paper. The material therefore emphasises the research process, scenario design logic, consolidated assumptions, and supplementary screening visuals that underpin the results and discussion.

Supplementary overview of the research process:

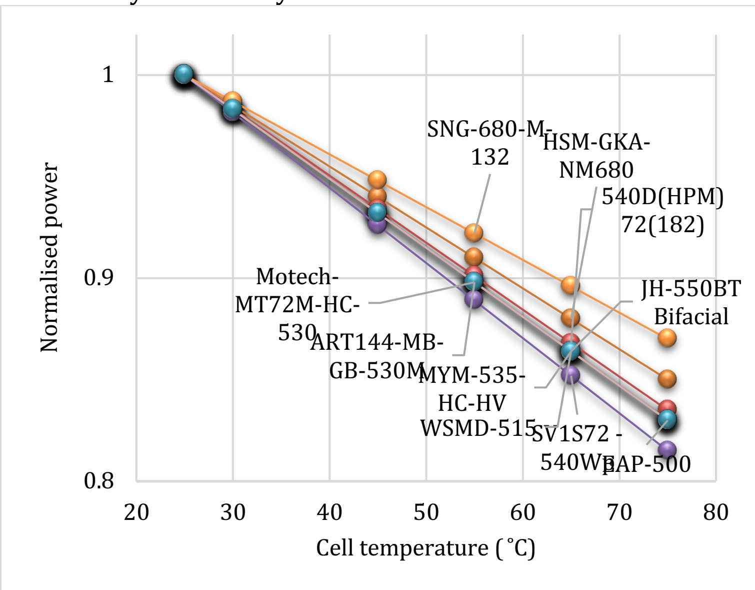
- Plant-provided hydro generation, reservoir storage, and technical data were assembled for NK2 and NK3, with 2024 retained as the principal operational year presented in the article.
- Hourly FPV output was generated in PVsyst for a set of candidate layouts, beginning with symmetric reference cases and then extending to asymmetric, downstream-only, and upstream-only variants.
- A solar-priority dispatch model was implemented in Excel to compare the baseline cluster delivery profile against coordinated FPV–hydropower operation under plant-level and cluster-level constraints.
- Daily reservoir updating was linked to hourly hydro dispatch through plant-specific water-to-energy conversion factors, while the hydraulic connection from NK3 to NK2 was represented as a one-day lag in the daily model.
- The 21 FPV designs were first screened against cluster water saving and export adequacy, then further screened using useful solar fraction, and finally interpreted through techno-economic indicators including CAPEX, NPV, IRR, LCOE, water-saving efficiency, and the NPV-to-CAPEX ratio.

Supplementary site-context image:

Google Earth satellite image showing the NK2–NK3 cascade and the relative positions of the two reservoirs

Solar module and inverter selection:

Before the FPV scenarios were simulated in PVsyst, solar modules and inverters available in PVsyst were examined for the most proper option. The purpose was not to identify a single universally optimal component, but to narrow the design space to realistic candidates for the case study. The module screening considered rated power, voltage and current characteristics, temperature coefficients, module area, technology type, and manufacturer availability in the PVsyst database.



Thermal derating curves of mono-facing modules (P/P25˚C)

From this visualised chart, JH-550BT Bifacial module was selected as the representative PV panel used in the case study. Note that the name “Bifacial” in this module did not affect its function as mono-facial because the module was configured as mono-facial.

All solar module candidates in PVsyst:

No.	Model (available now)	Pnom (STC) (W)	Voc (25˚) (V)	Vmpp (25˚) (V)	Isc (25˚) (A)	Impp (25˚) (A)	µPmax (power temp coeff) (%/˚C)	µVoc (V/˚C)	µIsc (%/˚C)	µIsc (A/˚C)	Module area (m2)	Technology	Manufacturer	Produced since
1	Motech-MT72M-HC-530	530	49.68	41.4	13.5	12.8	-0.34	-0.146	0.048	0.0065	2.583	mono-facial	ACS Enerji	2023
2	ASB-M10-144-520-Bifacial	520	48.6	41.18	13.41	12.8	-0.32	-0.127	0.04	0.0054	2.567	bifacial	Adani Solar	2025
3	CP9612MDGDC-540	540	49.6	41.93	13.73	12.88	-0.33	-0.142	0.05	0.0069	2.583	bifacial	Calypso	2023
4	EN182M-144D-535	535	49.7	41.76	13.57	12.81	-0.34	-0.145	0.05	0.0068	2.583	bifacial	Econess energy	2023
5	EAP-500	500	51.7	42.8	12.28	11.69	-0.34	-0.144	0.04	0.0049	2.385	mono-facial	Energy America	2023
6	HSM-GKA-NM680	680	48.2	40.6	17.72	16.77	-0.3	-0.122	0.05	0.0089	3.144	mono-facial	Huansheng Solar	2024
7	JH-550BT Bifacial	550	49.9	41.93	13.98	13.12	-0.34	-0.147	0.05	0.0070	2.581	mono-facial	Jakson Engineers	2023
8	540D(HPM)72(182)	540	49.42	41.6	13.85	12.98	-0.33	-0.139	0.047	0.0065	2.583	mono-facial	LESSO	2024
9	MYM-535-HC-HV	535	49.4	41.29	13.7	12.96	-0.34	-0.137	0.04	0.0055	2.584	mono-facial	MYM Solar Enerji	2023
10	SV1S72 - 540Wp	540	49.88	41	13.9	13.17	-0.37	-0.166	0.069	0.0096	2.581	mono-facial	Sengi Solar	2023
11	ART144-MB-GB-530M	530	49.4	41.55	13.48	12.75	-0.34	-0.146	0.05	0.0067	2.584	mono-facial	Sunart PV	2023
12	SNG-680-M-132	680	49.79	42.32	17.1	16.07	-0.26	-0.105	0.04	0.0068	3.106	mono-facial	Sungi Solar	2023
13	TS-BGT78-615	615	54.9	46.54	14.01	13.21	-0.3	-0.135	0.04	0.0056	2.794	bifacial	Thornova Solar	2024
14	WSMD-515	515	48.86	40.99	13.49	12.57	-0.34	-0.143	0.05	0.0067	2.574	mono-facial	Waaree Energies	2024
15	RH972MDGDC-540	540	49.6	41.93	13.73	12.88	-0.33	-0.142	0.05	0.0069	2.583	bifacial	Winhitech	2023

JH-550BT Bifacial module was selected among several candidates against parameters:

	mono-facial ACS Enerji Motech-MT72M-HC-530	bifacial Adani Solar ASB-M10-144-520-Bifacia	bifacial Calypso CP9612MDGDC-540	bifacial Econess energy EN182M-144D-535	mono-facial Energy America EAP-500	mono-facial Huansheng Solar HSM-GKA-NM680	mono-facial Jakson Engineers JH-550BT Bifacial
Tcell (˚C)	-0.34	-0.32	-0.33	-0.34	-0.34	-0.3	-0.34
25	1	1	1	1	1	1	1
30	0.983	0.984	0.9835	0.983	0.983	0.985	0.983
45	0.932	0.936	0.934	0.932	0.932	0.94	0.932
55	0.898	0.904	0.901	0.898	0.898	0.91	0.898
65	0.864	0.872	0.868	0.864	0.864	0.88	0.864
75	0.83	0.84	0.835	0.83	0.83	0.85	0.83

	mono-facial LESSO 540D(HPM)72(182)	mono-facial MYM Solar Enerji MYM-535-HC-HV	mono-facial Sengi Solar SV1S72 - 540Wp	mono-facial Sunart PV ART144-MB-GB-530M	mono-facial Sungi Solar SNG-680-M-132	bifacial Thornova Solar TS-BGT78-615	mono-facial Waaree Energies WSMD-515	bifacial Winhitech RH972MDGDC-540
Tcell (˚C)	-0.33	-0.34	-0.37	-0.34	-0.26	-0.3	-0.34	-0.33
25	1	1	1	1	1	1	1	1
30	0.9835	0.983	0.9815	0.983	0.987	0.985	0.983	0.9835
45	0.934	0.932	0.926	0.932	0.948	0.94	0.932	0.934
55	0.901	0.898	0.889	0.898	0.922	0.91	0.898	0.901
65	0.868	0.864	0.852	0.864	0.896	0.88	0.864	0.868
75	0.835	0.83	0.815	0.83	0.87	0.85	0.83	0.835

Inverter screening considered maximum DC voltage, MPPT operating range, nominal AC output, conversion efficiency, MPPT segmentation, DC/AC sizing practicality and temperature-derating behaviour.

Manufacturer	**GE Power Conversion**	**Siel**	**Siemens**	**WSTECH GmbH**	**Wynnertech**
Model	**LV5-1560**	**Soleil-SPX-200K-3ph**	**Sinacon PV1000**	**APS1000-PV-1-550-5**	**ALBA 4x 1500 550Vac**
Prod since	2020	2024	2017	2017	2017
Vdc, max (V)	1500	1500	1500	1500	1500
Vmppt, min (V)	851	500	802	804	800
Vmppt, nom (V)	N/A	N/A	N/A	N/A	N/A
Vmppt, max (V)	1300	1500	1500	1425	1200
Idc, max (A)	3000	N/A	1600	1220	4000
Pac, nom (kVA/kW)	2760	200	1000	1000	2669
Pac, max (kW)	3120	225	1000	1000	2936
Grid V	600	800	550	550	550
Hz	50, 60	50, 60	50, 60	50, 60	50, 60
Max eff (%)	98.9	99	98.77	98.77	98.78
CEC/EURO eff (%)	98.7	98.7	98.67	98.67	98.68
#MPPT	1	6	1	1	4
#DC inputs	24	18	8	8	24
Nb of inverters	5	69	14	14	5.3
Nb of strings	1356	1415	1356	1356	1356
Modules in series	24	23	24	24	24
Pdc,max (kW) → **DC/AC allowable**	N/A	N/A	2000	2000	N/A
Temp limits (Pnom up to °C; overpower at °C)	30, 25	50, 25 but not enabled	40, 25 but not enabled	40, 25 but not enabled	50, 25 not enabled
Technology	Transformerless	Transformerless	Without LV Transfo, 3Level NPC-IGB	Without LV Transfo, 3Level NPC-IGBT	Efficient and grid-friendly
Night consumption (W)	0	0	80	80	100
Pnom ratio	1.3	1.3	1.28	1.28	1.28
PVsyst warnings (yes/no + text)	The array Isc value is greater than the inverter maximum input current (i.e. (i.e. 3000.0 A/input)). (Info, not significant)	The array has 1415 strings to be distributed onto 414 MPPT inputs	no warning	The array Isc value is greater than the inverter maximum input current (i.e. (i.e. 1220.0 A/input)). (Info, not significant)	no warning
Comments	-GE also derates early (30°C), which is a poor match for Attapeu -Show DC current warnings	Technically OK, but **69 inverters** changes the plant architecture a lot (more AC combining, more O&M points, more MPPT segmentation).	-Passes current (no warning) -Wide MPPT max (1500 V) with good margin -Pnom up to 40°C with explicit derating points -14 inverters (reasonable utility architecture)	-Show DC current warnings	-Passes current -Fewer inverters (simpler plant) -But MPPT max = 1200 V is tighter → I must confirm my cold Vmp stays below 1200 V (use PVsyst sizing report).

Sinacon PV1000 of Siemens was selected as the representative inverter for the case study upon several components considered

Additional data and assumption notes:

The article presents the coordinated NK2–NK3 analysis using the 2024 operational dataset. During model development, additional tests were explored to examine alternative hydrological conditions, export-cap interpretations, and layout configurations; however, the main article retains a concise version of these assumptions to preserve focus. The two tables below consolidate the principal modelling and economic assumptions used in the coordinated simulations.

Consolidated modelling assumptions used in the coordinated cascade simulations

(Source: authors' compilation from plant-provided operational data (2024), feasibility material (Power-China Chengdu Engineering Corporation Limited, 2021), and the coordinated Excel model)

Assumption	Value	Comment
Plants represented	NK3 upstream; NK2 downstream	Cascade pair on the same river system
Hydropower capacity	NK3 = 54 MW; NK2 = 66 MW	Installed plant capacities used in the case study
Reservoir storage (approx.)	NK3 = 471 million m^3; NK2 = 71.4 million m^3	Observed system context used in the article
Distance between reservoirs	≈ 13 km	Used to interpret physical routing lag
Hydraulic lag in model	One day in the daily storage model	Physical travel time is about 5 h, but storage is updated daily
Dispatch priority	Solar first, hydro second	Hydro is reassigned if one reservoir reaches minimum operating level
Plant-level caps	NK3 = 54 MW; NK2 = 66 MW	Conservative local combined hydro-plus-FPV caps
Cluster-level export cap	120 MW	Joint export consistency constraint at the Bo Y interconnection
Water-to-energy factor	α_NK3 = 4.05 m^3/kWh; α_NK2 = 4.11 m^3/kWh	Derived from plant-provided unpublished operational data
Storage bounds	Minimum and maximum operating storage applied	Spill occurs when raw storage exceeds the maximum
Scenario families	Symmetric, NK2-only, NK3-only, and asymmetric layouts	21 coordinated FPV designs tested

Economic inputs used in the PVsyst techno-economic evaluation

Parameter	Value	Note
Project life	30 years	Operation period used in PVsyst economic evaluation
Debt / equity	70% / 30%	Feasibility-style financing assumption
Loan interest	6%	Used in PVsyst evaluation
Loan term	10 years	With 1-year grace period
Tariff	0.0695 USD/kWh	Based on feasibility material
VAT	0%	Economic assumption
Profit tax / royalty	20% / 5%	Economic assumption
Discount rate	8%	Used for comparison metrics
Inflation rate	0%	Economic assumption
Dynamic investment	713.70 USD/kWdc	All-in investment basis
Maintenance	0.3% of fixed assets per year	Operating cost assumption
Insurance	0.1% for first 10 years; 0.2% thereafter	Operating cost assumption
Materials	0.769 USD/kW-year	Operating cost assumption
Other expenses	10.59 USD × kWp	Operating cost assumption

(Source: authors' compilation from feasibility material (Power-China Chengdu Engineering Corporation Limited, 2021) and PVsyst economic inputs)

Expanded FPV design matrix:

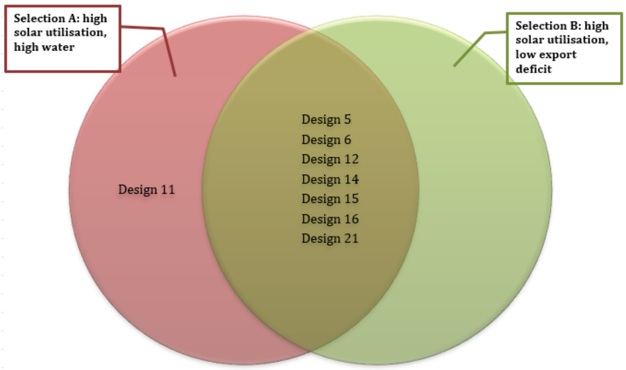
The full coordinated design space assessed during the shortlisting stage is summarised below. These layouts include the symmetric reference cases, single-reservoir deployment options, and asymmetric combinations used to test how FPV placement changes export adequacy and cluster water saving.

Design matrix for the 21 coordinated FPV scenarios

Design code	Scenario family	NK3 layout	NK2 layout
Design 1	Symmetric	South facing, 10° tilt, 5% coverage	South facing, 10° tilt, 5% coverage
Design 2	Symmetric	South facing, 10° tilt, 10% coverage	South facing, 10° tilt, 10% coverage
Design 3	Symmetric	East-West, 10° tilt, 5% coverage	East-West, 10° tilt, 5% coverage
Design 4	Symmetric	East-West, 10° tilt, 10% coverage	East-West, 10° tilt, 10% coverage
Design 5	NK2-only	FPV NK3=0	East-West, 10° tilt 5% coverage
Design 6	NK2-only	FPV NK3=0	East-West, 10° tilt, 10% coverage
Design 7	NK2-only	FPV NK3=0	East-West, 10° tilt, 2% coverage
Design 8	NK3-only	East-West, 10° tilt, 5% coverage	FPV NK2=0
Design 9	NK3-only	East-West, 10° tilt, 10% coverage	FPV NK2=0
Design 10	NK3-only	East-West, 10° tilt, 2% coverage	FPV NK2=0
Design 11	Asymmetric east-west	East-West, 10° tilt, 0.5% coverage	East-West, 10° tilt 5% coverage
Design 12	Asymmetric east-west	East-West, 10° tilt, 1% coverage	East-West, 10° tilt, 5% coverage
Design 13	Asymmetric east-west	East-West, 10° tilt, 2% coverage	East-West, 10° tilt, 5% coverage
Design 14	Asymmetric east-west	East-West, 10° tilt, 0.5% coverage	East-West, 10° tilt, 10% coverage
Design 15	Asymmetric south-facing	FPV NK3=0	South-facing, 10° tilt, 5% coverage
Design 16	Asymmetric south-facing	FPV NK3=0	South-facing, 10° tilt, 10% coverage
Design 17	Asymmetric south-facing	FPV NK3=0	South-facing, 10° tilt, 2% coverage
Design 18	Asymmetric south-facing	South-facing, 10° tilt, 0.5% coverage	South-facing, 10° tilt, 5% coverage
Design 19	Asymmetric south-facing	South-facing, 10° tilt, 1% coverage	South-facing, 10° tilt, 5% coverage
Design 20	Asymmetric south-facing	South-facing, 10° tilt, 2% coverage	South-facing, 10° tilt, 5% coverage
Design 21	Asymmetric south-facing	South-facing, 10° tilt, 0.5% coverage	South-facing, 10° tilt, 10% coverage

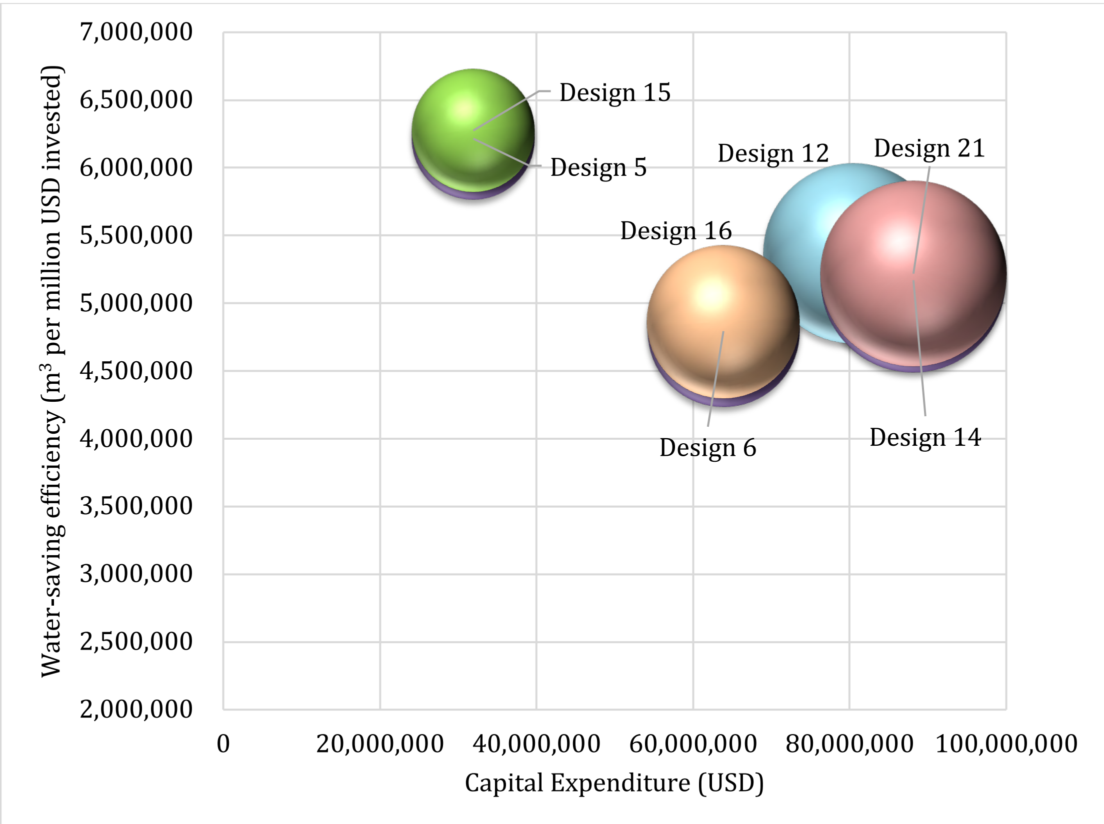
Additional screening visuals

The main article retains the most essential trade-off figures. The supplementary figures below provide two additional views that were useful during interpretation: an overlap visual of the two technical screening pathways and a supporting economic visual that compares water-saving efficiency against capital expenditure.



Overlap of the two technical screening pathways used in the shortlisting process
(Source: authors' visualisation based on the shortlisting analysis)

Selection A retained layouts with high solar utilisation and comparatively high water saving. Selection B retained layouts with high solar utilisation and comparatively low export deficit. Their overlap identifies the common technically preferred set before the final techno-economic interpretation.



Additional economic visual comparing water saving, water-saving efficiency, and CAPEX among shortlisted designs
(Source: authors' visualisation based on shortlisted design outputs)

This supporting visual reinforces the distinction between water-priority and cost-efficient layouts. Designs with larger total water saving do not always deliver the strongest water-saving benefit per unit of investment, because higher-capacity deployments also require larger CAPEX.

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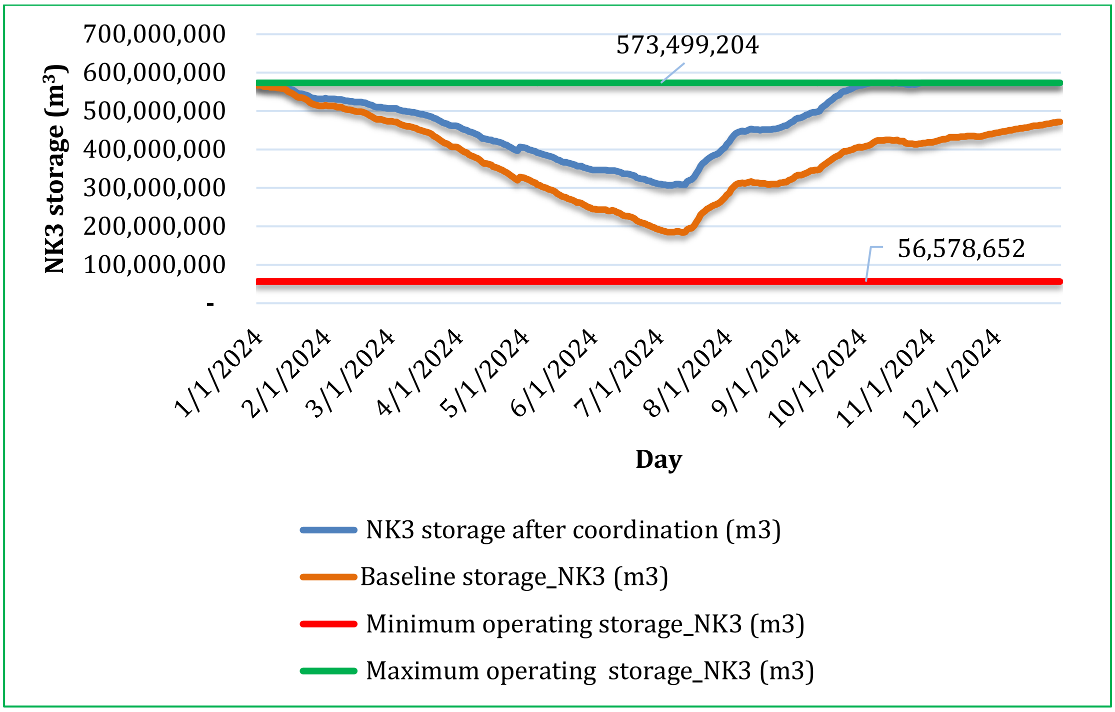
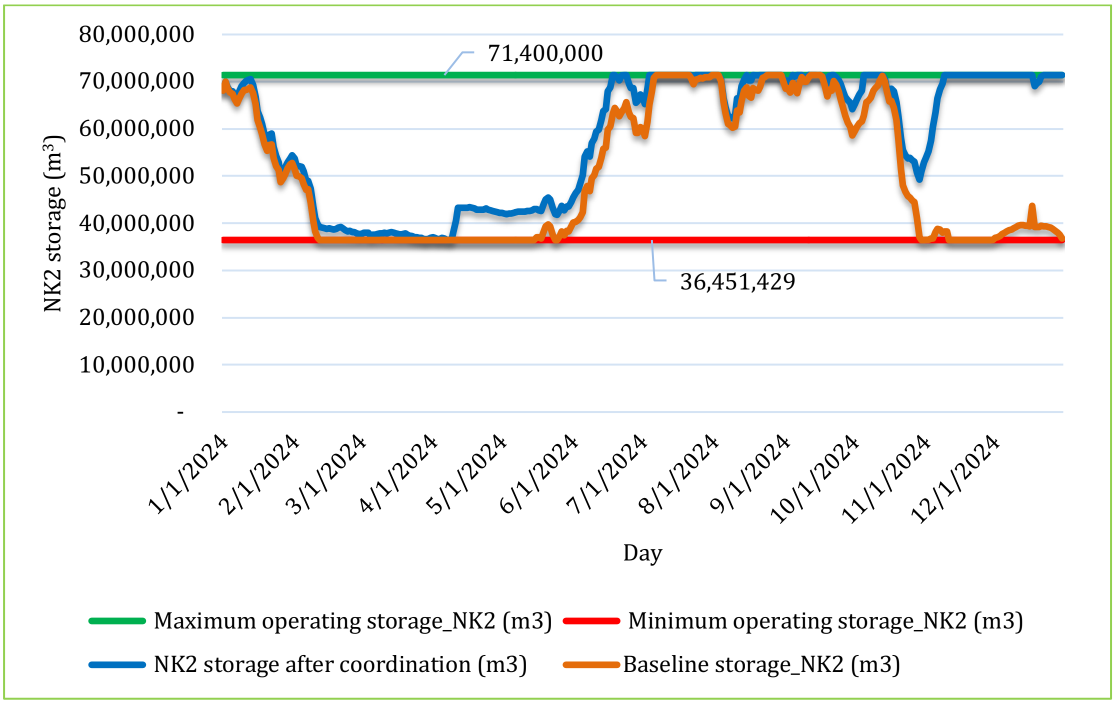
Baseline-versus-updated reservoir trajectories:

The main article presents only the most compact storage figure. The updated figures below show more explicitly how the baseline reservoir trajectories were compared with updated trajectories after coordinated FPV deployment.



Comparison of baseline and updated storage trajectories for NK3 under coordinated FPV deployment



Comparison of baseline and updated storage trajectories for NK2 under coordinated FPV deployment

Relationship to the main article:

- The consolidated assumptions tables support the methods section by making the modelling and economic inputs explicit in one place.
- The expanded 21-design matrix provides the full scenario basis from which the main article's results and shortlisting narrative were derived.
- The overlap visual clarifies how the preferred designs emerged from two separate technical screening approaches before being reduced to the final shortlist.
- The additional economic visual supplements the article's main CAPEX-versus-water-saving chart by distinguishing absolute hydrological benefit from investment efficiency.

References:

Power-China Chengdu Engineering Corporation Limited, 2021. Technical consultancy and feasibility study for the Nam Kong 2 and Nam Kong 3 ground mounted and floating solar project. Power-China Chengdu Engineering Corporation Limited, Sichuan, China.