Supplementary Information *for*

Environmental and geographic constraints shape global pumped hydro for long-duration storage

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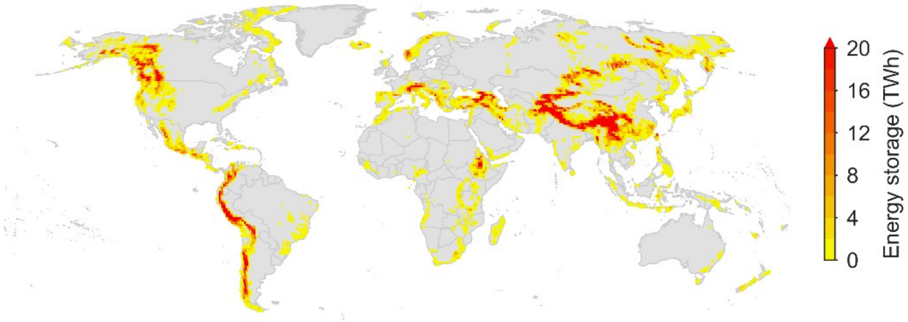

Fig. S1. Spatial distribution of global PHS potential. The PHS potential is gridded as a 1-degree global raster. Gray areas indicate regions with no PHS resources.

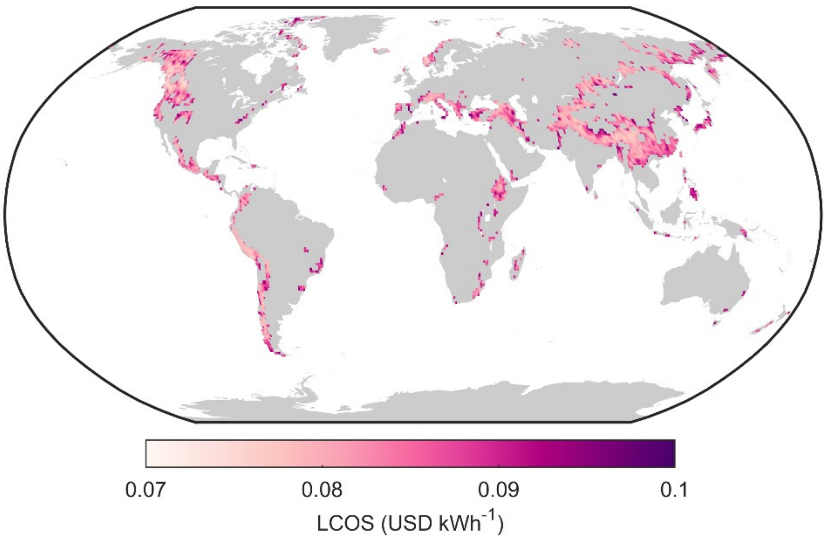

Fig. S2. Global distribution of LCOS for PHS. Gray areas indicate regions with no PHS potential.

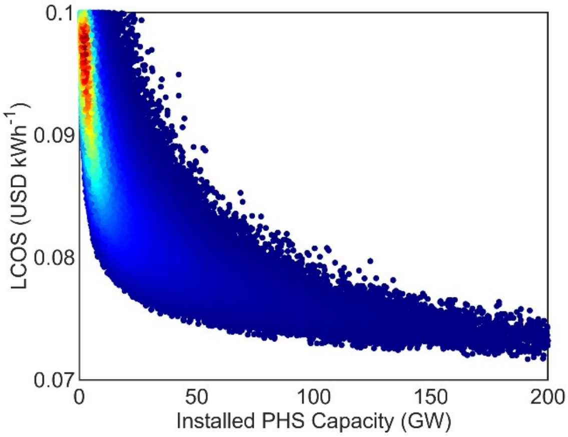

Fig. S3. Relationship between installed PHS capacity and LCOS. Each point represents a candidate PHS project.

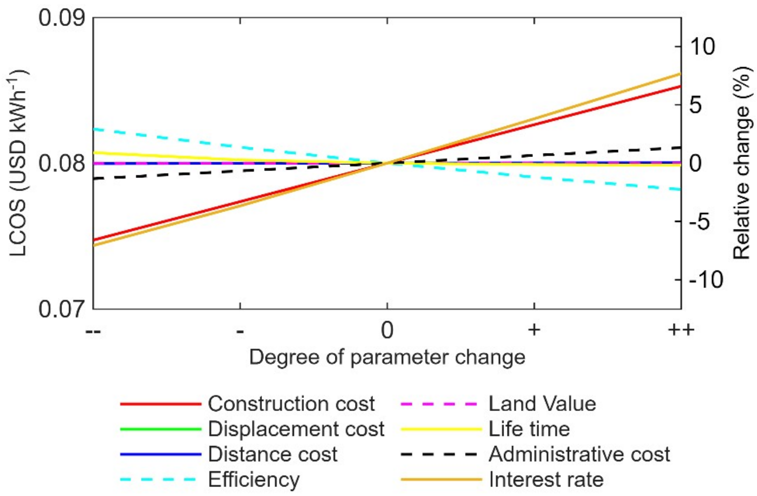

Fig. S4. Sensitivity analysis of key parameters of PHS costs. The detailed parameter adjustment scheme is shown in Table S3.

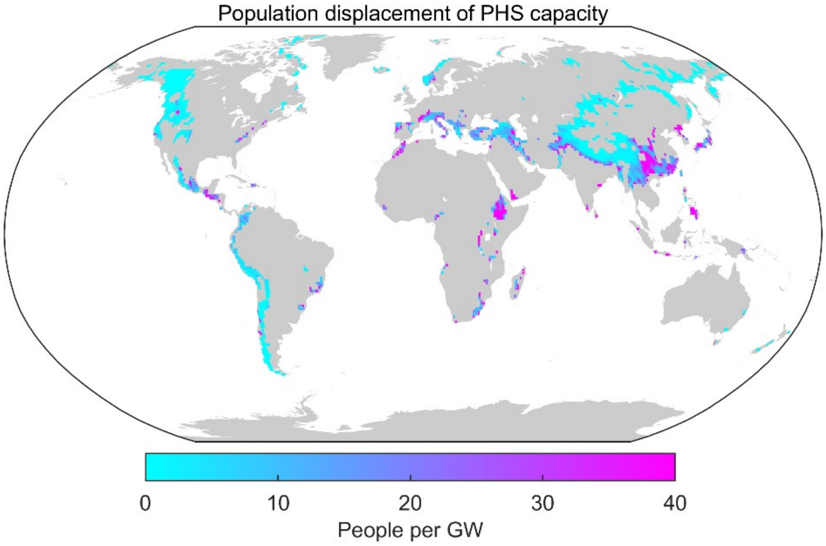

Fig. S5. Population displacement intensity associated with PHS capacity.

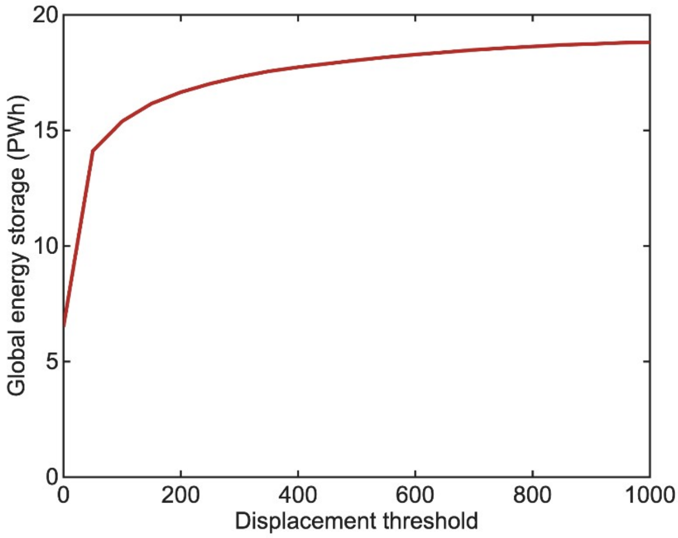

Fig. S6. Global PHS energy storage potential under varying displacement thresholds.

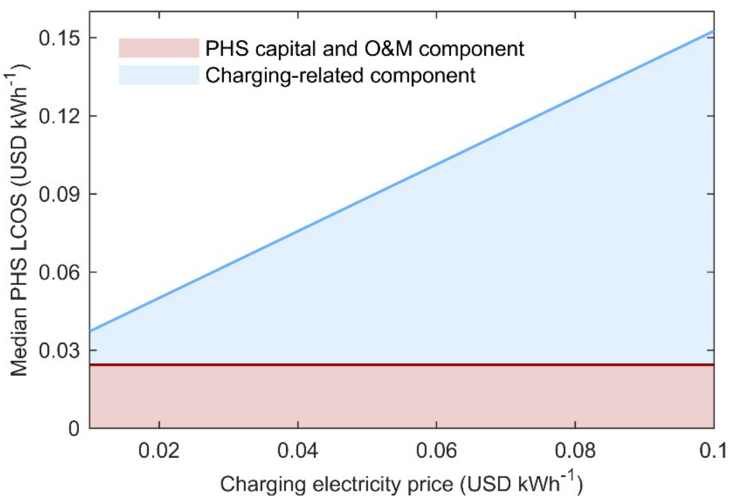

Fig. S7. Decomposition of PHS LCOS with respect to charging electricity price.

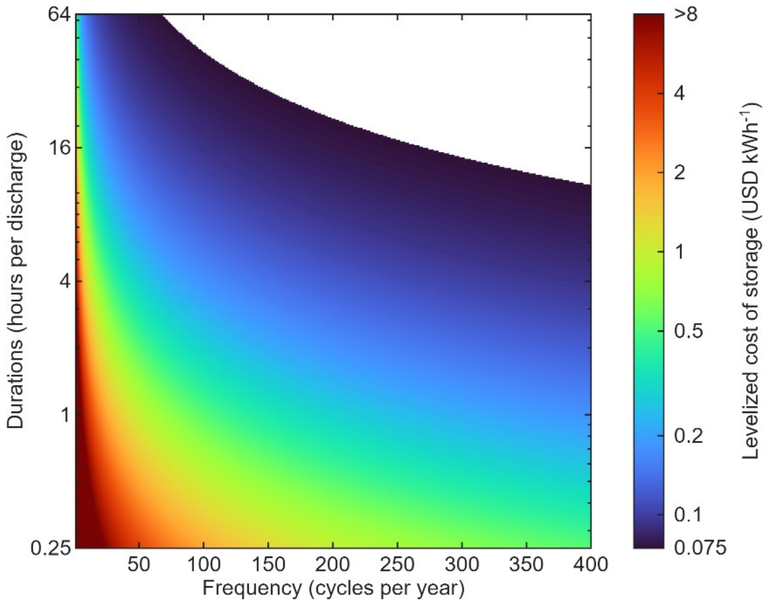

Fig. S8. LCOS of PHS across discharge duration and cycling frequency.

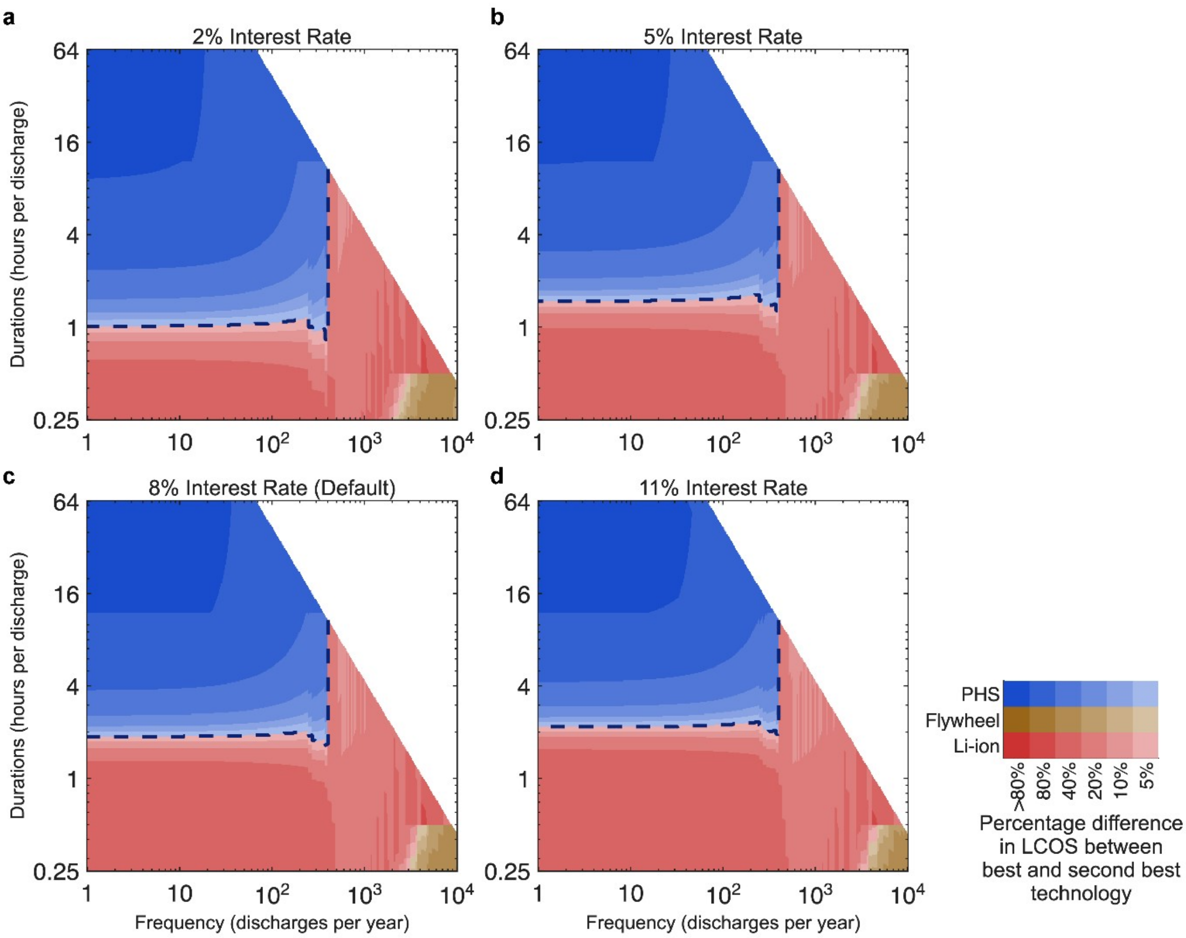

Fig. S9. Cost competitiveness of energy storage technologies across discharge duration and cycling frequency under different interest rates. (**a**) 2% interest rate. (**b**) 5% interest rate. (**c**) 8% interest rate. (**d**) 11% interest rate. Each panel shows the technology with the lowest LCOS under a given combination of discharge duration and annual cycling frequency. Colors indicate the percentage cost difference between the most competitive technology and the second-best option.

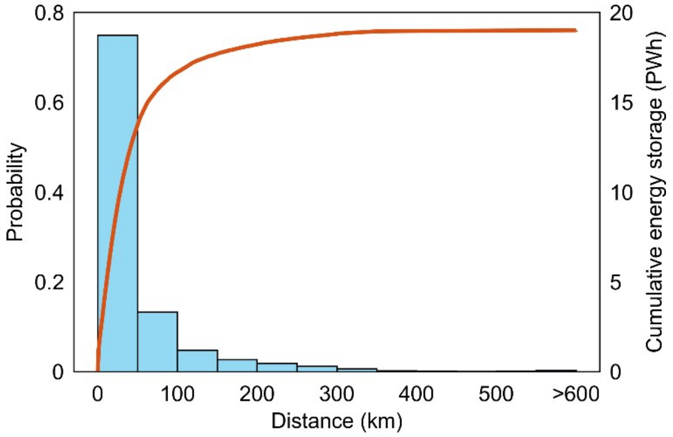

Fig. S10. Distance of PHS sites from high-voltage grids, with probability distribution and cumulative energy storage.

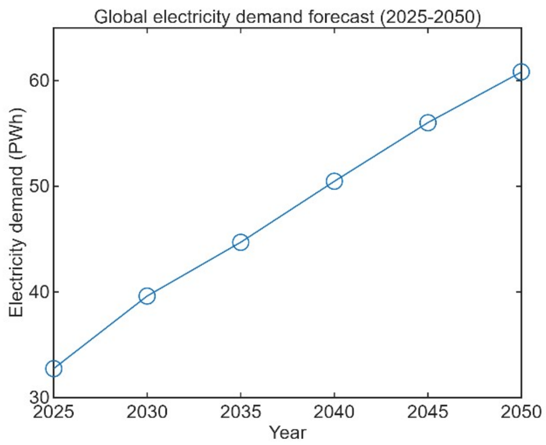

Fig. S11. Projected growth of global electricity demand from 2025 to 2050 (*ref. 28*).

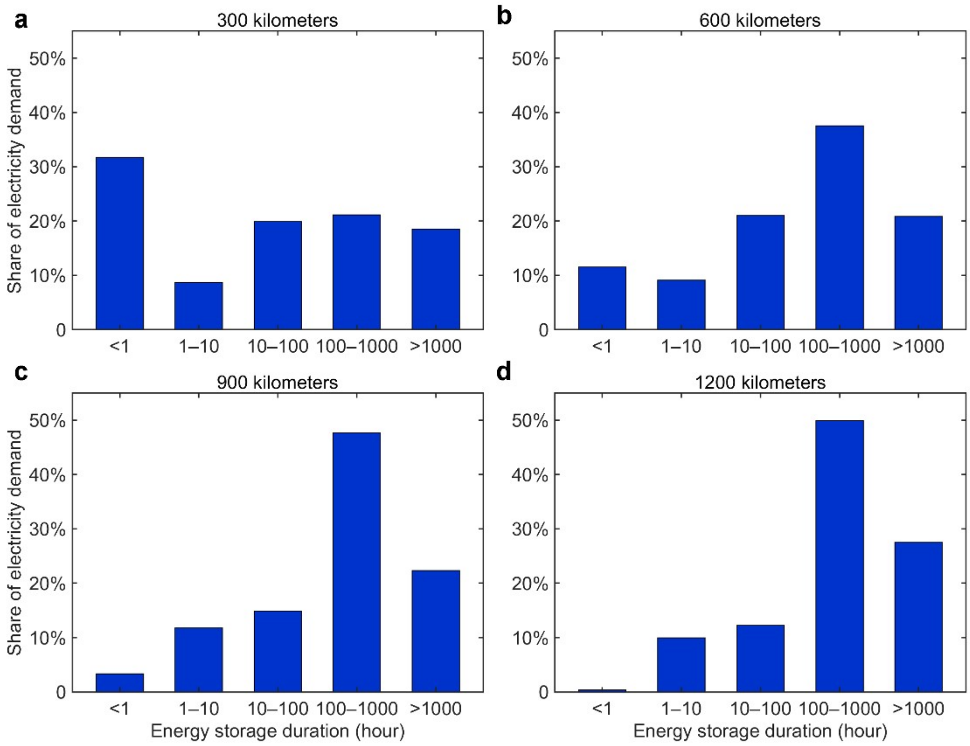

Fig. S12. Distribution of global electricity demand by accessible PHS storage duration under different service radius. (**a**) 300 km transmission distance. (**b**) 600 km transmission distance. (**c**) 900 km transmission distance. (**d**) 1,200 km transmission distance.

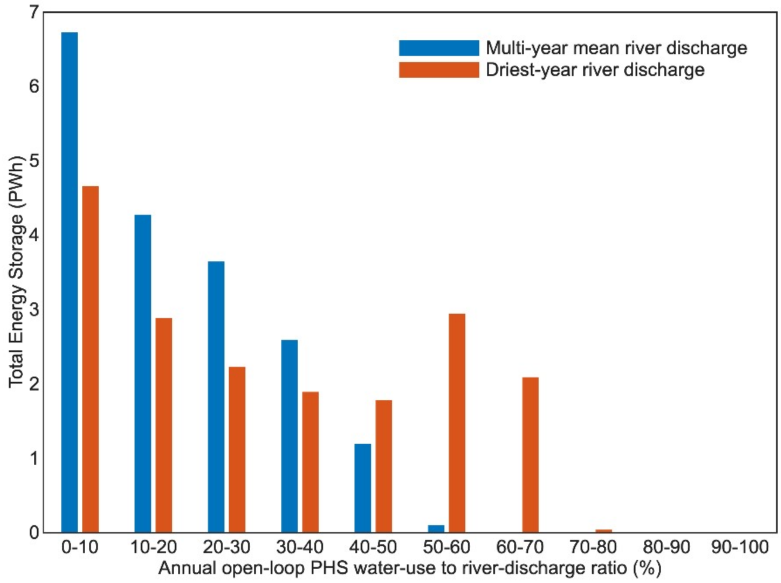

Fig. S13. Open-loop PHS water-use ratios under mean and driest-year river discharge.

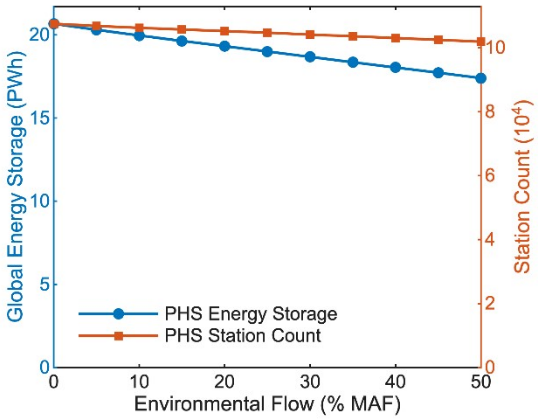

Fig. S14. Sensitivity of open-loop PHS potential and station count to environmental-flow requirements.

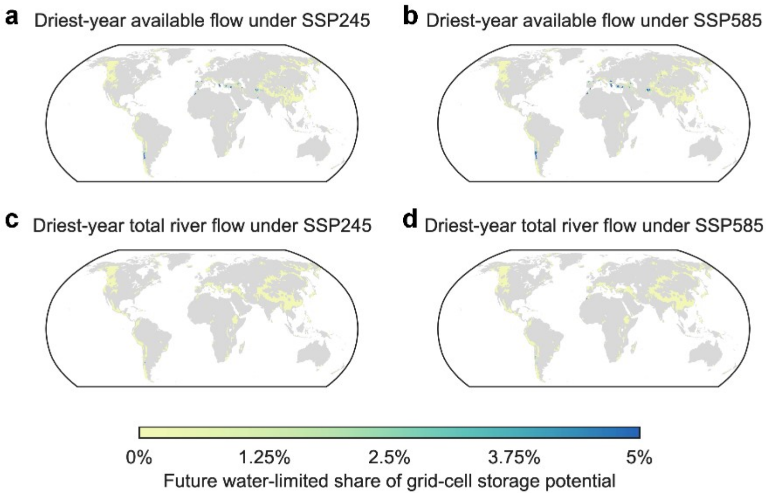

Fig. S15. Future water-limited share of open-loop PHS resources under SSP245 and SSP585. (**a**) Future water-limited PHS share based on driest-year available flow under SSP245. (**b**) Future water-limited PHS share based on driest-year available flow under SSP585. (**c**) Future water-limited PHS share based on driest-year total river flow under SSP245. (**d**) Future water-limited PHS share based on driest-year total river flow under SSP585. Available flow is defined as total river flow minus environmental-flow requirements.

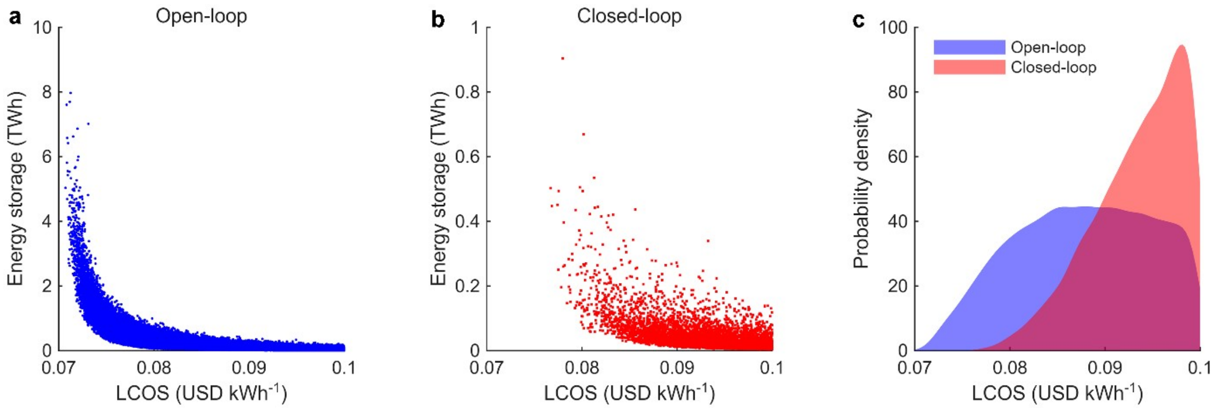

Fig. S16. Systematic differences in storage scale and cost between open-loop and closed-loop PHS. (**a**) Relationship between energy storage capacity and LCOS for open-loop PHS sites. (**b**) Relationship between energy storage capacity and LCOS for closed-loop PHS sites. (**c**) Probability density distributions of LCOS for open-loop and closed-loop PHS.

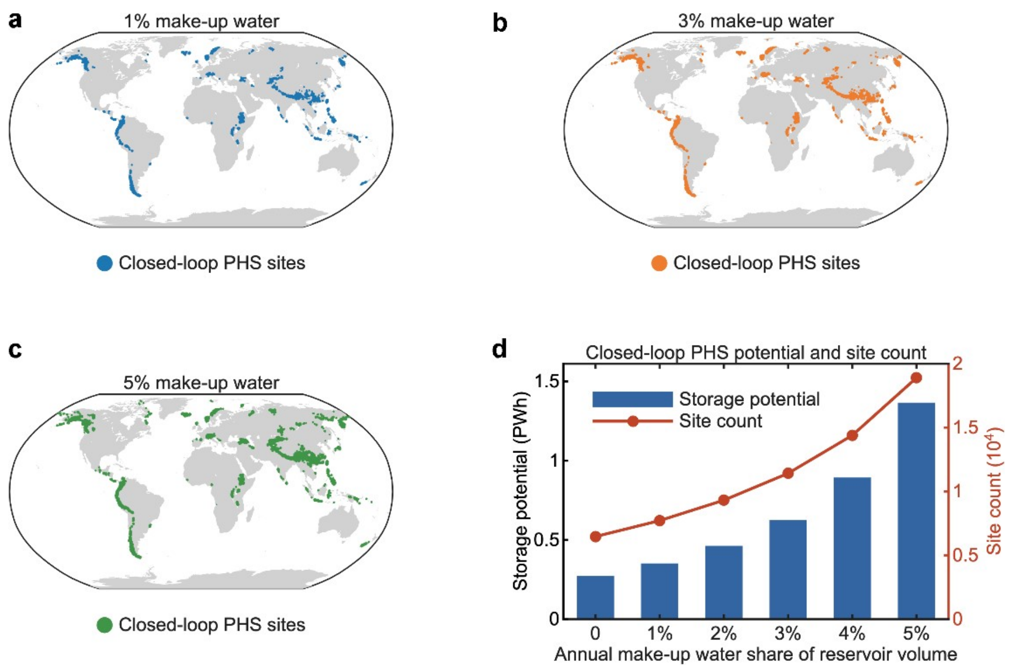

Fig. S17. Spatial distribution and global potential of closed-loop PHS under make-up water allowances. (**a–c**) Sites with annual make-up water equivalent to 1%, 3% and 5% of reservoir volume. (**d**) Global storage potential and site count under 0–5% make-up water.

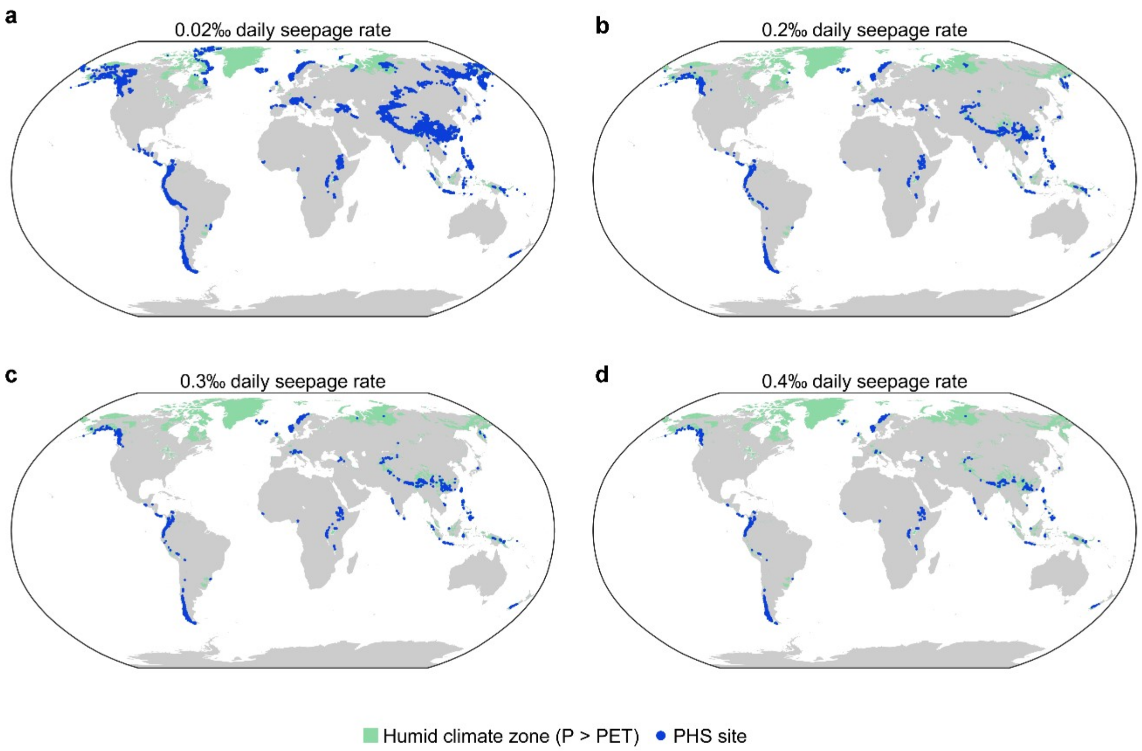

Fig. S18. Global distribution of closed-loop PHS sites under different reservoir seepage rates. (**a**) 0.02‰ daily seepage rate. (**b**) 0.2‰ daily seepage rate. (**c**) 0.3‰ daily seepage rate. (**d**) 0.4‰ daily seepage rate. Green shading indicates humid climate zones where precipitation exceeds potential evapotranspiration (P > PET), and blue dots denote identified closed-loop PHS sites.

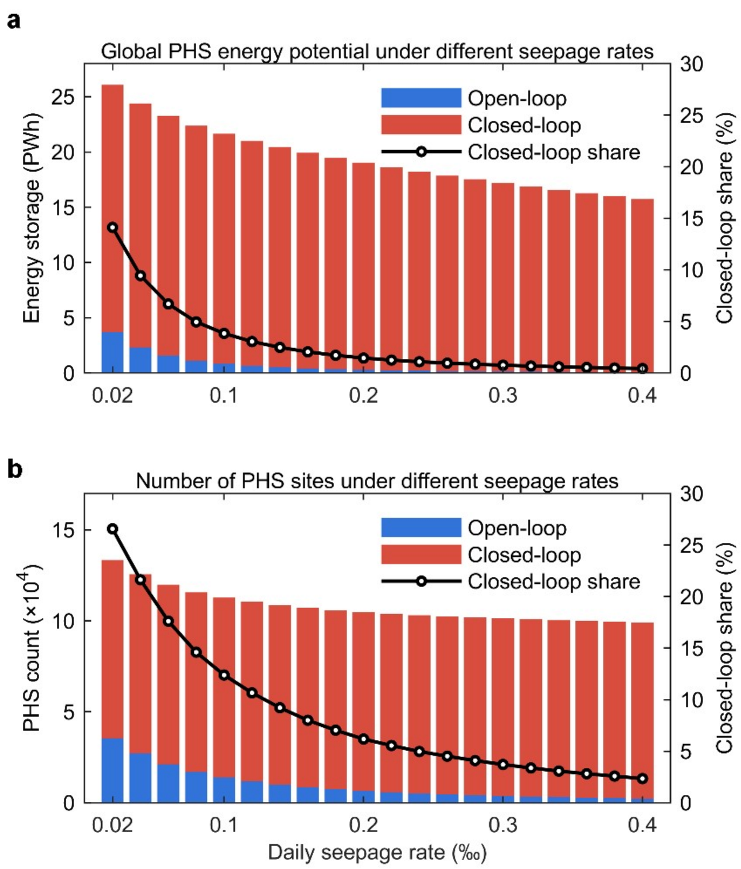

Fig. S19. Sensitivity of global PHS potential and site availability to reservoir seepage rate. (**a**) Global PHS energy storage potential under different daily seepage rates. (**b**) Number of PHS sites under different daily seepage rates

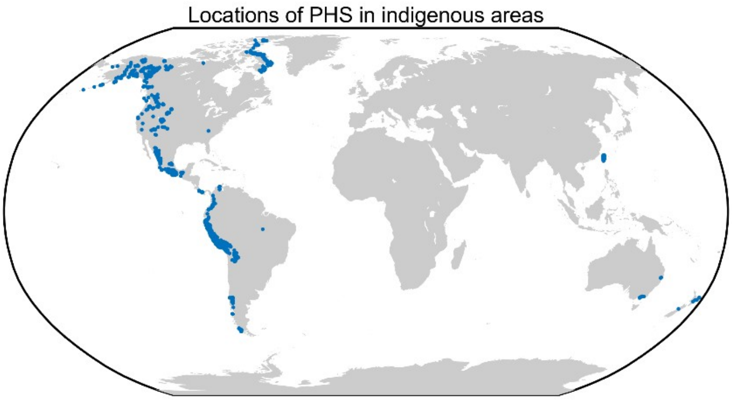

Fig. S20. Global distribution of potential PHS sites within Indigenous territories.

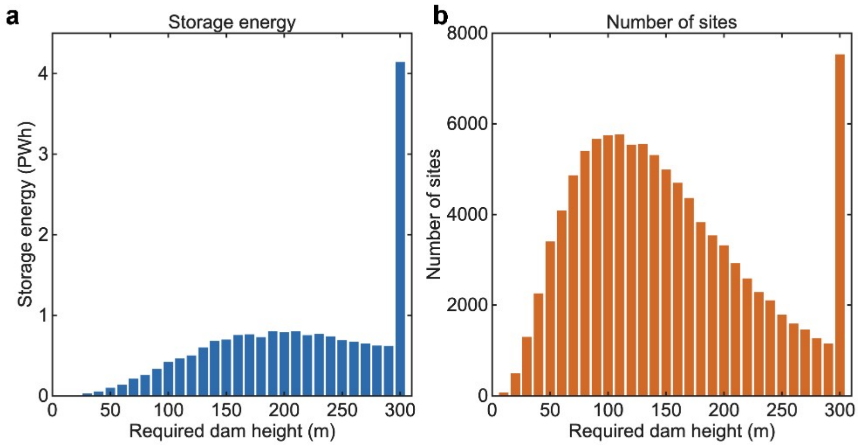

Fig. S21. Storage energy and site count by required dam height. (**a**) Storage energy by required dam height. (**b**) Number of PHS sites by required dam height.

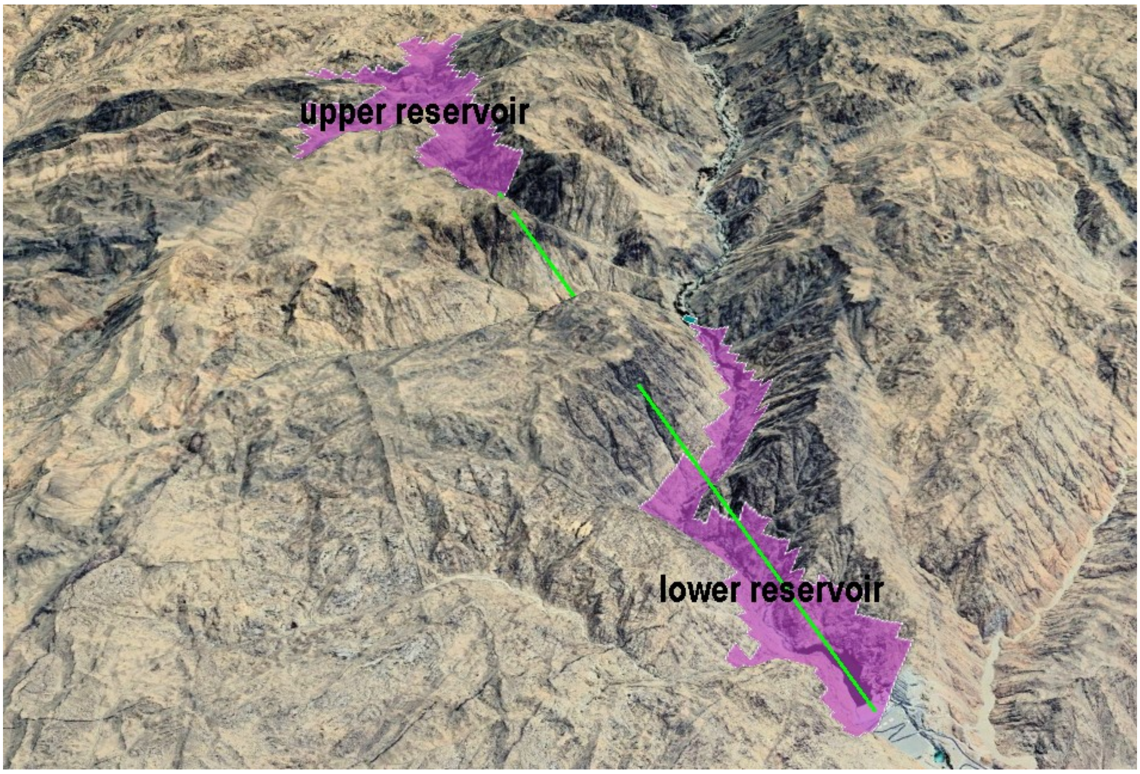

Fig. S22. Visualization of optimized PHS site locations.

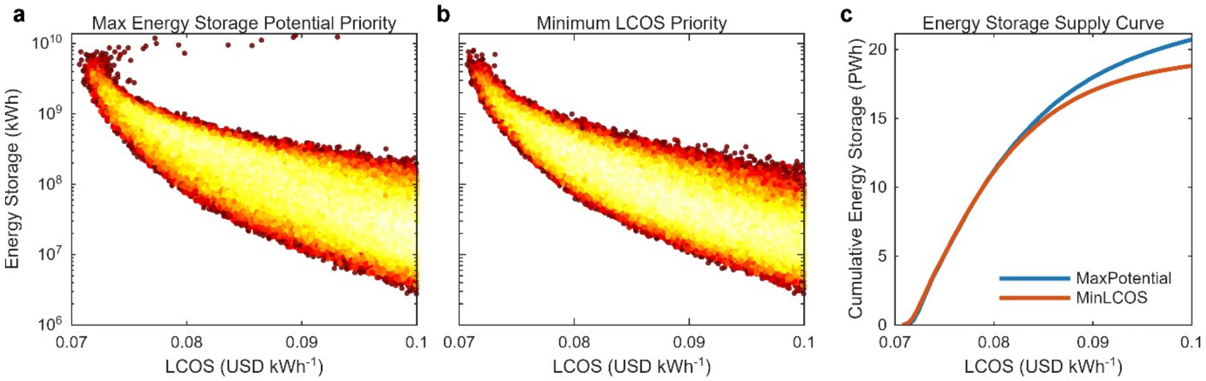

Fig. S23. PHS site selection under maximum-storage and minimum-LCOS prioritization. (**a**) Candidate sites prioritized by maximum energy storage potential. (**b**) Candidate sites prioritized by minimum LCOS. (**c**) Global PHS storage supply curves under the two prioritization strategies.

Table S1. Pumped hydroelectric storage resource, LCOS, storage duration, and per capita energy storage in the countries and territories that have PHS resources. The units for total energy storage and per capita pumped storage are terawatt-hours (TWh) and kilowatt-hours (kWh), respectively. Storage duration is the equivalent number of hours that PHS resources in each country or territory could meet projected 2050 electricity demand. LCOS indicates the average LCOS (USD kWh^{-1}) of PHS within each country or territory. Uncertainty ranges are derived from MERIT-DEM.

Country	Energy storage	LCOS	Storage duration	Per capita energy storage
China	5568 ± 744	0.079	3346	3919
Russia	2162 ± 293	0.080	3969	15270
Canada	1900 ± 237	0.078	6591	51488
Peru	969 ± 127	0.079	>8760	30709
India	722 ± 89	0.080	2129	551
United States	706 ± 113	0.080	445	2157
Chile	665 ± 86	0.079	>8760	36937
Turkey	507 ± 84	0.080	7867	6246
Kyrgyzstan	475 ± 60	0.080	>8760	81957
Afghanistan	449 ± 63	0.080	>8760	14734
Pakistan	391 ± 47	0.080	>8760	1715
Colombia	330 ± 51	0.082	>8760	6806
Ethiopia	292 ± 58	0.081	>8760	2689
Bolivia	284 ± 39	0.079	>8760	24963
Mexico	281 ± 48	0.081	3400	2208
Nepal	263 ± 33	0.081	>8760	8774
Argentina	262 ± 41	0.080	>8760	5787
Tajikistan	256 ± 32	0.080	>8760	29377
Italy	192 ± 26	0.080	1399	3103
Norway	188 ± 35	0.079	2422	36232
Iran	183 ± 34	0.082	3015	2180
Myanmar	150 ± 25	0.082	>8760	2721
Georgia	139 ± 16	0.079	>8760	28267
Ecuador	135 ± 21	0.082	>8760	8112
Kazakhstan	100 ± 15	0.081	3030	5272
Austria	76 ± 9	0.080	2772	8655
France	74 ± 10	0.080	317	1132
Switzerland	59 ± 8	0.080	2188	7007
Japan	53 ± 8	0.084	131	422
Spain	52 ± 9	0.082	461	1068
Iceland	47 ± 7	0.078	7587	143929
Vietnam	46 ± 8	0.083	2543	472

Country	Energy storage	LCOS	Storage duration	Per capita energy storage
Uzbekistan	43 ± 6	0.081	2122	1403
Azerbaijan	40 ± 7	0.082	6257	3999
Guatemala	38 ± 7	0.083	>8760	2283
Greece	37 ± 7	0.083	1969	3509
Mongolia	37 ± 8	0.082	>8760	11694
North Korea	32 ± 7	0.087	>8760	1254
Philippines	31 ± 6	0.085	2363	292
Albania	29 ± 5	0.080	>8760	9603
Romania	28 ± 5	0.084	>8760	1319
Indonesia	27 ± 6	0.086	831	104
Bosnia and Herzegovina	26 ± 6	0.081	6511	6836
Iraq	25 ± 4	0.082	1520	633
New Zealand	22 ± 4	0.084	653	4676
Honduras	21 ± 5	0.083	>8760	2365
Morocco	21 ± 5	0.085	3026	607
Armenia	20 ± 4	0.083	>8760	6600
Tanzania	20 ± 6	0.085	7731	352
South Africa	18 ± 5	0.084	236	318
Yemen	17 ± 4	0.085	>8760	599
Lesotho	17 ± 4	0.082	>8760	8655
Brazil	16 ± 5	0.085	101	78
Madagascar	16 ± 5	0.083	>8760	604
Montenegro	15 ± 3	0.079	4645	26385
Democratic Republic of the Congo	15 ± 4	0.084	7265	153
Laos	14 ± 3	0.086	>8760	1882
Eritrea	12 ± 2	0.083	>8760	2085
Bulgaria	12 ± 3	0.086	828	1699
Timor-Leste	12 ± 2	0.083	>8760	8827
Venezuela	11 ± 2	0.082	722	401
Cameroon	11 ± 3	0.084	6204	389
Haiti	8 ± 1	0.083	3763	755
Sweden	8 ± 2	0.080	86	794
Papua New Guinea	7 ± 2	0.087	>8760	1056
Algeria	7 ± 2	0.087	717	173
Macedonia	7 ± 2	0.086	3099	3344
Serbia	7 ± 2	0.084	478	976
Bhutan	6 ± 1	0.085	>8760	7854
Portugal	6 ± 2	0.083	345	594
New Caledonia	6 ± 1	0.085	>8760	21850

Country	Energy storage	LCOS	Storage duration	Per capita energy storage
Slovenia	6 ± 1	0.084	1089	2758
Croatia	6 ± 2	0.081	1065	1345
Kenya	6 ± 1	0.086	2641	107
Nigeria	5 ± 1	0.085	1078	24
Kosovo	5 ± 1	0.083	>8760	2411
Ukraine	5 ± 1	0.086	58	105
Lebanon	5 ± 1	0.085	1485	685
Costa Rica	4 ± 1	0.086	2075	877
Guinea	4 ± 2	0.086	>8760	331
Panama	4 ± 1	0.087	1709	995
Angola	3 ± 1	0.087	1523	98
Sri Lanka	3 ± 1	0.084	1275	136
Burundi	3 ± 1	0.087	>8760	262
Dominican Republic	3 ± 1	0.088	885	290
Svalbard	2 ± 0	0.086	>8760	1173958
United Kingdom	2 ± 0	0.085	12	35
Zambia	2 ± 1	0.077	910	133
El Salvador	2 ± 0	0.085	1165	324
Australia	2 ± 1	0.090	14	82
Thailand	2 ± 1	0.087	66	29
Uganda	2 ± 0	0.090	>8760	39
South Korea	2 ± 0	0.090	11	30
Mozambique	1 ± 1	0.084	635	50
Zimbabwe	1 ± 1	0.086	752	102
Syria	1 ± 0	0.086	124	53
Malawi	1 ± 0	0.086	>8760	46
Saudi Arabia	1 ± 0	0.090	12	27
Swaziland	1 ± 0	0.084	>8760	831
Germany	1 ± 0	0.086	3	11
Nicaragua	1 ± 0	0.091	483	140
Rwanda	1 ± 0	0.091	>8760	64
Jordan	1 ± 0	0.086	235	63
Cuba	1 ± 0	0.088	>8760	54

Table S2. The cost calculation formula for PHS systems.

Cost component	Equation	Ref.
	Power components Cost	
Turbine (USD)	$p_1 = 1.943P_T^{0.7643}10^6$ $P_T = Q_D h\rho g\eta 10^{-6}$	*22-24*
Power station (NOK)	$p_2 = (0.4948Q_D + 1.7)10^6\ (Q_D \leq 50m^3s^{-1})$ $p_2 = (-0.0006Q_D^2 + 0.67Q_D - 6.95)10^6\ (50m^3s^{-1} < Q_D \leq 500m^3s^{-1})$ $p_2 = 178.05 \times 10^6\ (Q_D \geq 500m^3s^{-1})$	*22-24*
Electro-technical equipment (NOK)	$p_3 = 3.9142P_T^{0.6622}10^6$	*22-24*
Fish passage (USD)	$p_4 = 1.3e^6(10^3P_T)^{0.56}$	*22-24*
Miscellaneous (NOK)	$p_5 = (-38.795logQ_D + 309.89)P_T10^3$	*22-24*
Power line connection (NOK)	$p_6 = Lp_p$	*22, 31*
Piping–headrace tunnel (NOK)	$p_7 = 219.99A_t + 13658(L_p - h)m_t$ $m_t = 0.0054(L_p10^{-3})^2 - 0.0039(L_p10^{-3}) + 0.9671$	*22-24*
Piping–penstock (NOK)	$p_8 = (6D_t + 9.4h)\eta_p10^3$	*22-24*
	Storage components cost	
Dam (NOK)	$p_9 = 0.72D_H^{1.8}D_L10^3$	*22-24*
Land loss cost	$p_{10} = A * land\ value$.	*65-67*
Population displacement (USD)	$p_{11} = 5 * GDP/capita$.	*68*
	Composite cost and LCOS	
Seismic hazard cost (USD)	$p_{12} = 0.05(\sum_{i=1}^{9} p_i)$	
Owner cost (USD)	$p_{14} = 0.2(\sum_{i=1}^{12} p_i)$	
Operation and maintenance (USD)	$p_{15} = 0.02(\sum_{i=1}^{12} p_i)$	
LCOS	$LCOS = \frac{C_I + \sum_{t=0}^{n}\left(M_t(1+r)^{-t}\right) + \sum_{t=0}^{n}(C_{\mathrm{ch}}(1+r)^{-t})}{\sum_{t=0}^{n}(E_E(1+r)^{-t})}$	*22-24*

Note:

P_T: turbine capacity (MW)

Q_D: design discharge ($m^3 s^{-1}$)

h: hydraulic head (m)

ρ: density of water (kg m^{-3})
g: acceleration due to gravity, 9.81 m s^{-2}
L: shortest distance to powerline (km)
p_p: 1,600,000 USD km^{-1}
A_t: cross-section area of tunnels (m^2)
L_p: length of the pipes (m)
D_t: tunnel diameter (m)
D_H: dam height (m)
D_L: dam length (m)
A: the inundation area of the PHS reservoir.
The LCOS calculation method is in *Section* 4.3.4

Table S3. Sensitivity analysis parameter adjustment scheme (*ref. 22*).

	--	-	**Default**	+	++
Interest rate	4%	6%	8%	10%	12%
Owners rate	10%	15%	20%	25%	30%
Construction cost	0.50 ×	0.75 ×	1 ×	1.25 ×	1.5 ×
Distance cost	0.50 ×	0.75 ×	1 ×	1.25 ×	1.5 ×
Displacement cost	1 × GDP	3 × GDP	5 × GDP	7 × GDP	9 × GDP
Lifetime	35 yr	45 yr	55 yr	65 yr	75 yr
Efficiency	68%	73%	78%	83%	88%
Land Value	0.50 ×	0.75 ×	1 ×	1.25 ×	1.5 ×

Table S4. Environmental flow scenarios. MAF (the mean annual flow), MMF (the mean monthly flow) (*ref. 72*).

Scenario	Description
Tennant	($MMF \leq MAF$) 0.2 times of MAF ($MMF > MAF$) 0.4 times of MAF
Tessmann	($MMF \leq 0.4MAF$) MMF ($MMF > MAF$) 0.4 times of MMF ($0.4MAF < MMF \leq MAF$) 0.4 times of MAF