

# Strategizing renewable energy transitions to preserve sediment transport integrity

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Hydropower is vital for climate mitigation by enabling low-carbon energy systems, but hydropower dams also trap sediment, a crucial resource for ecosystems and climate adaptation along downstream coastlines. Here we present a multisectoral integrated water–sediment–energy planning framework that fully internalizes the impacts of hydropower expansion, both on energy system costs and on foregone ecosystem services from reduced sediment supply for the Mekong River Basin. Our analysis indicates that full development of large hydropower could reduce sediment flows to the Mekong Delta by  $41.2 \pm 6.6$  megatonnes per year ( $75 \pm 9\%$ ). However, strategically replacing 19 high-sediment-trapping hydropower plants with solar, wind and energy storage alternatives could preserve up to 98% of sediment supply, with only a 4–6% (US\$15.7–26.0 billion) increase in energy system costs over 2020–2050. Crucially, when sediment-related benefits—valued at US\$12–28 million per megatonne per year—are considered, the additional costs of preserving sediment supply are nearly offset. The proposed framework offers a transferable approach to support sustainable low-carbon energy transitions while safeguarding sediment-dependent ecosystems worldwide.

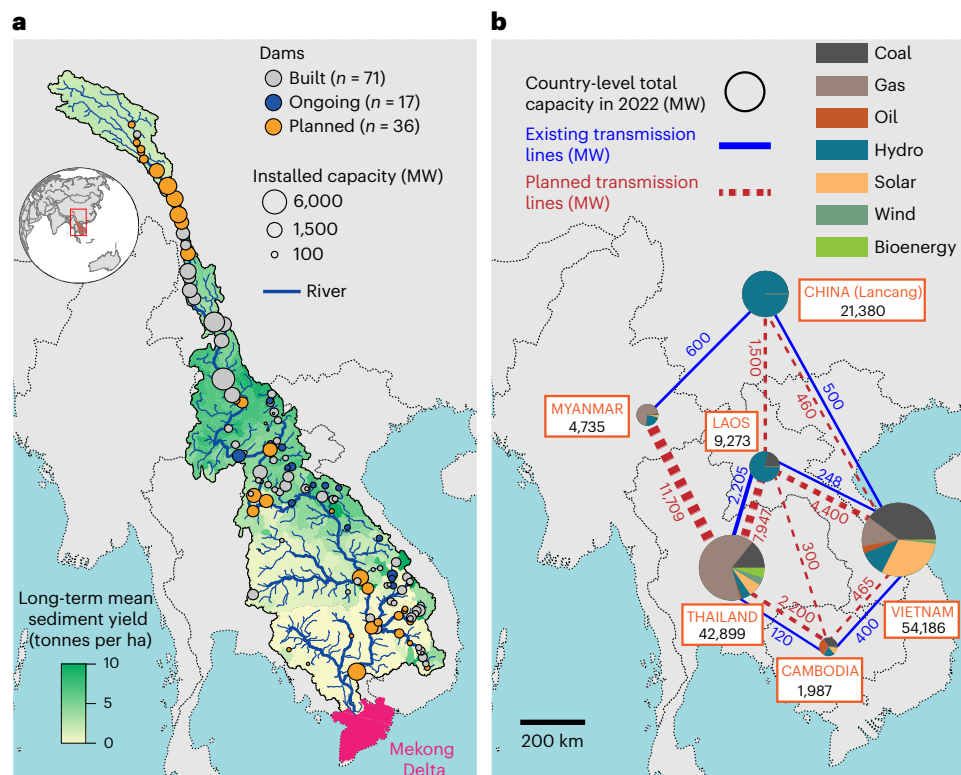
Hydropower, as a low-carbon, reliable and cost-competitive renewable energy source, plays a pivotal role in the global clean energy transition<sup>1</sup>. In 2023, hydropower accounted for 14% of global electricity supply and 36% of renewable energy generation<sup>2</sup>. Moreover, hydroelectricity provides almost one-third of the necessary flexibility services<sup>3</sup>, making it indispensable for power grid stability. Meeting the anticipated three-fold increase in global electricity demand by 2050<sup>4,5</sup> while achieving net-zero emissions will likely require an additional 400 to 850 gigawatts (GW) of hydropower capacity<sup>6,7</sup>, a 33–71% increase over current levels. This projected increase is grounded in the perceived vast generation potential of hydropower<sup>8,9</sup> as well as its flexibility<sup>10</sup>, crucial to compensate for the intermittency of future variable renewable energy (VRE), primarily solar photovoltaic (PV) and wind power<sup>11,12</sup>.

Although hydropower plays an important mitigation role in stabilizing power grids and decarbonizing energy portfolios, the dams

and reservoirs associated with large facilities pose substantial risks for downstream riverine, deltaic and coastal environments<sup>13,14</sup>. Hydropower dams fragment rivers, preventing downstream conveyance of sediment and other materials, hindering the migration of aquatic organisms and thus disrupting processes that support vital ecosystem services<sup>15</sup>. For instance, sediment trapped in dams would otherwise help mitigate land loss and subsidence<sup>16</sup>, maintain coastal landforms<sup>17</sup>, support marine ecosystems<sup>18</sup>, preserve biodiversity<sup>19</sup> and ensure the stability and productivity of coasts and oceans. These impacts of dams are the motivation for our analysis, because although hydropower development aids in climate mitigation, its sediment trapping negatively impacts climate resilience and adaptation goals<sup>20–22</sup> and thus creates a trade-off problem for solving global development challenges.

This mitigation-adaptation trade-off is particularly acute in the Mekong River Basin (MRB)<sup>15,18,23</sup>, a transboundary river basin with a total

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**Fig. 1 | Geography and energy infrastructure in the MRB. a**, Built, ongoing and planned hydropower dams sized by installed capacity in megawatts (MW) and estimated sediment yields from 552 subregions based on hydrological model simulations from 1962 to 2005<sup>27</sup>. **b**, Energy mix for the six riverine countries

and cross-country power transmission line capacity in the MRB, with all values reported in MW. Note: Our analysis only considers China's hydropower generation from the upper Mekong River (also called Lancang River; see details in Methods).

hydropower generation potential of 268,000 gigawatt-hours (GWh) per year<sup>24</sup>. Over half of this potential has already been developed, with 71 dams built across 124 identified dam sites (Fig. 1), mostly over the past 2 decades<sup>24</sup>. Sediment trapping in these dams, when combined with other disruptive factors including sand mining<sup>25</sup> and variable tropical cyclone activity<sup>26</sup>, has led to a 108–120 megatonnes (Mt) per year (67–75%) reduction in sediment reaching the Mekong Delta<sup>15,16,24,27</sup>.

The Mekong Delta is home to approximately 20 million people. It is one of the world's most productive coastal regions, contributing 2.5% of global rice production<sup>18</sup>, or more than half of Vietnam's staple crops and 90% of its rice exports<sup>28,29</sup>. With 53 additional large hydropower plants under construction or planned for completion by 2030<sup>24</sup>, sediment trapped in reservoirs behind dams could equate to an ~90% loss of the delta's land area by 2100, compounded by rising sea levels<sup>16</sup>. Additionally, reduced sediment loads disrupt river processes and nutrient dynamics in the lower Mekong Basin, leading to an estimated US\$20 ± 8 million loss in rice and fish production per megatonne of sediment lost each year<sup>30</sup>.

Unlike non-substitutable sediment, crucial for maintaining delta stability and adaptation, hydropower can be substituted with other renewables, such as the increasingly cost-competitive VRE paired with energy storage technologies<sup>31,32</sup>. However, the strategic implementation of integrated renewable systems is challenging due to the considerable spatial and temporal variability of each energy type. This complexity often impedes the development of environmentally sustainable and economically viable policies, as well as the cross-country cooperation needed to balance the trade-offs associated with hydropower. Existing literature on strategic hydropower planning is largely generation-driven, focusing on optimal dam placement to maximize energy generation<sup>24,33,34</sup>. In comparison, conventional energy systems planning typically emphasizes economic cost-optimality to meet

climate commitments but fails to internalize the negative externalities associated with renewable energy development<sup>35–37</sup>. Although some studies have begun to explore joint energy–environment trade-offs<sup>38–40</sup>, few have directly optimized hydropower portfolios and operations within a fully integrated energy system planning model. In particular, existing studies commonly treat hydropower generation as an exogenous input, thus neglecting its inherent operational flexibility and its critical role in balancing VRE<sup>10</sup>. This incongruence relates, in part, to the lack of integrated water–sediment–energy modelling tools, which should link basin-scale dam planning with energy capacity expansion models. Such tools should look beyond generation metrics, accounting for the multiscale and distributional impacts of dams on sediment trapping, meanwhile recognizing the flexibility and complementarity of hydropower with VRE<sup>41</sup>.

To address these challenges, we herein develop an integrated modelling framework that combines strategic hydropower planning with energy system planning (Methods and Extended Data Fig. 1). This approach allows us to (1) understand broader environmental externalities of energy systems that meet different socioeconomic needs and climate commitments; (2) evaluate the cost implications of environmental impacts, such as sediment trapped by hydropower dams; and (3) explore strategies for substituting high-impact hydropower with VRE, along with the associated cost implications, considering both energy perspectives and the ecosystem services provided by sediment. We demonstrate this framework for the MRB, analysing the trade-offs between energy system costs and sediment supply—both of which are influenced by hydropower portfolios.

To explore how climate policy ambition and regional electricity cooperation shape these trade-offs, we designed 16 scenarios that systematically combine 4 carbon emission pathways and 4 levels of transboundary electricity transmission integration (Table 1). The emission

**Table 1 | Experiment and scenario design**

Scenario type	Scenario name	Scenario description
Decarbonization targets <sup>42</sup>	1.5°C-compatible (T1.5°C)	This scenario represents climate policies and commitments aligned with the Paris Agreement's goal of limiting global warming to 1.5°C. It assumes that national policies are fully consistent with the 1.5°C target, reflecting the highest level of climate ambition.
	2°C-compatible (T2°C)	This scenario assumes a two-thirds probability that global warming remains below 2°C by the end of the century. Although current climate policies and commitments are not fully aligned with the Paris Agreement's 1.5°C target, they could achieve this goal with moderate policy enhancements. It reflects a level of ambition that, while falling short of 1.5°C compatibility, represents notable progress toward emissions reductions.
	3°C-compatible (T3°C)	This scenario assumes a two-thirds probability that global warming remains below 3°C by the end of the century. It reflects a trajectory where current climate policies and commitments are insufficient to meet the Paris Agreement's 1.5°C target. Substantial policy enhancements would be required to achieve meaningful emissions reductions and align with more ambitious climate mitigation goals.
	4°C-compatible (T4°C)	This scenario assumes a two-thirds probability that global warming reaches 4°C by the end of the century. It represents a pathway where current climate policies and commitments are highly insufficient to meet the Paris Agreement's 1.5°C target, often resulting in rising rather than declining emissions. This trajectory reflects limited mitigation efforts, posing severe risks to global climate stability.
Transboundary electricity transmissions	EXISTING	Only existing transboundary interconnections (4,073 MW) are considered, based on ref. 64 (Supplementary Table 1).
	PLANNED	New transmissions are restricted to the current planned capacity of 28,981 MW, based on ref. 64 (Supplementary Table 1).
	LIMITED	Transmissions among the MRB countries can be optimized, but for domestic energy security, the electricity imports of each country should not exceed one-third of each country's total electricity demand <sup>65,66</sup> . Additionally, China's electricity exports should not surpass one-third of its domestic hydropower generation in the Lancang River Basin. This is to factor in China's own energy security concerns <sup>67</sup> . A sensitivity analysis of these import/export thresholds is provided in Supplementary Fig. 23.
	OPTIMIZED	Transmissions among lower Mekong countries can be optimized without any limit <sup>36</sup> .

scenarios represent a range of policy stringency based on global warming limits (1.5°C, 2°C, 3°C and 4°C), using nationally determined emission caps derived from Climate Action Tracker (CAT) data<sup>42</sup>. The transmission scenarios reflect degrees of cross-border coordination, including existing interconnection (EXISTING), planned expansion (PLANNED), capped power trade with security constraints (LIMITED) and fully co-optimized transmission and generation planning (OPTIMIZED). Together, these scenarios capture plausible futures for the MRB and allow us to assess how energy, environment and cooperation objectives can be jointly managed in transboundary river basins. To further examine the robustness of model outcomes, we conducted a comprehensive uncertainty analysis accounting for key factors such as investment cost, renewable resource availability, sediment trapping efficiency and electricity demand (Supplementary Note 1). For each of the 16 scenarios, we simulated 729 uncertainty realizations in the energy system model and 1,000 realizations in the sediment routing model, reporting key results (for example, cost, generation mix, sediment delivery) as mean  $\pm$  one standard deviation.

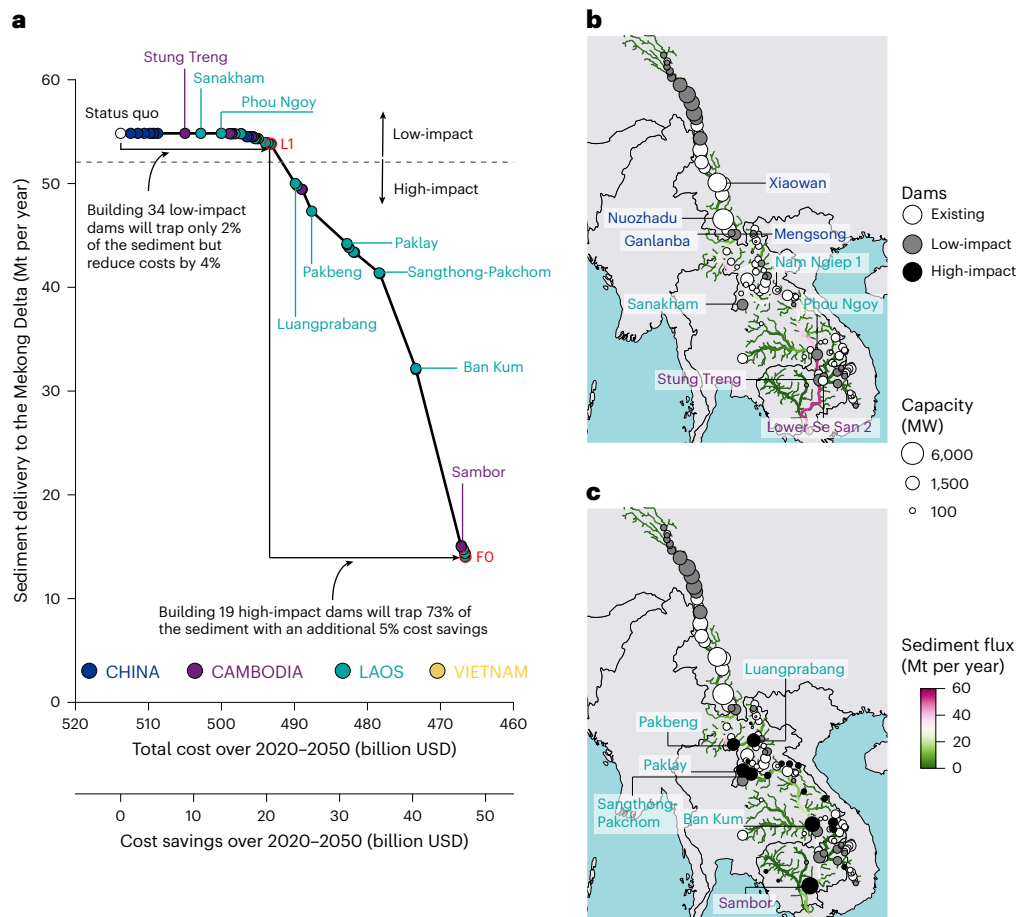
## Results

### Opportunities for cost savings and sediment benefits

A full buildout of hydropower reduces total energy system costs compared to a scenario without hydropower expansion, primarily due to its cost-competitiveness and flexibility services. In the most ambitious scenario (that is, 1.5°C decarbonization target with optimized transboundary transmission expansion), completing 53 planned and ongoing hydropower dams with a total capacity of 27 GW can save US\$45.7  $\pm$  13.4 billion in total system costs over the planning horizon (2020–2050), compared to a scenario where hydropower is not expanded and increasing energy demands are met by VRE and energy storage technologies (Fig. 2a and Extended Data Fig. 2). Such cost savings are primarily driven by the low-cost flexibility services provided

by cheap hydropower. Without additional hydropower expansion, a 1.5°C-compatible (T1.5°C) MRB energy system will require 750  $\pm$  219 GW of VRE (Supplementary Fig. 1). In a high-VRE power grid where VRE will make up 80% of total installed capacity in 2050, existing hydropower is insufficient to compensate for the intermittency of VRE. Consequently, meeting electricity demand would require the installation of 150  $\pm$  34 GW of lithium-ion (Li-ion) battery storage. However, a full buildout of hydropower with 27 GW from all 53 planned and ongoing dams would result in the installation of only 126 GW of Li-ion battery storage ( $\pm$ 31 GW) and 655 GW of VRE ( $\pm$ 195 GW), representing average reductions of 24 GW and 95 GW, respectively, compared to the scenario without hydropower expansion (Supplementary Fig. 1).

While reducing energy systems costs, a full buildout of hydropower would also reduce sediment delivery to the Mekong Delta by 75  $\pm$  9%, from 55.0  $\pm$  4.9 Mt per year (in the scenario without hydropower expansion) to 13.8  $\pm$  5.1 Mt per year (in the scenario with full hydropower development) (Fig. 2a and Extended Data Fig. 2), consistent with previous estimates<sup>16,24</sup>. However, at the plant level, not all hydropower dams would have the same sediment-trapping effect, and different expansion strategies for hydropower can lead to vastly different cumulative impacts on sediment even with the same amount of added hydropower generation. We thus performed a strategic optimization of the future dam development sequence (Fig. 2a), identifying which hydropower portfolio would have the lowest impacts on sediment budget. Along the Pareto-optimal expansion sequence, we identified 34 'low-impact' hydropower projects (18 GW). It should be noted that we define 'low-impact' here and throughout merely with regard to sediment, but those dams might of course lead to other impacts: for example, on fish migration and displacement of people. If only low-impact dams are developed, the resulting reduction in sediment delivery would be limited to just 2%, from 55.0 Mt per year ( $\pm$ 4.9 Mt per year) to 53.8 Mt per year ( $\pm$ 3.4 Mt per year), while still achieving



**Fig. 2 | Impacts of hydropower expansion on the energy system costs and sediment supply in the Mekong.** **a**, Trade-off between sediment supply and energy system costs. Each marker represents adding one more dam in the hydropower portfolio along the optimal sequence. Here we only show the trade-off for the most ambitious scenario, where transboundary transmissions are optimized and the 1.5 °C-compatible decarbonization target is met.

The dashed line separates low-impact versus high-impact hydropower plants with a threshold of 5% reduction in annual sediment supply compared to the status quo. **b,c**, Spatial distribution of sediment flux along the river network for two selected hydropower development portfolios: low-impact (L1; **b**) and full-development (FO; **c**). Uncertainties related to Fig. 2 can be found in Extended Data Fig. 2 and Supplementary Figs. 1 and 2.

cost savings of US\$19.6 billion ( $\pm$  US\$7.3 billion) over the planning horizon, from US\$511.3 billion ( $\pm$  US\$122.3 billion) to US\$491.7 billion ( $\pm$  US\$116.0 billion), compared to the scenario without hydropower expansion (Fig. 2a and Extended Data Fig. 2). This translates to an estimated marginal impact of approximately 0.05 Mt per year reduction in sediment delivery per billion US dollars (USD) saved.

Although the remaining 9 GW from 19 high-impact hydropower plants along the Pareto-optimal sequence (dams below the horizontal dotted line in Fig. 2a) can further reduce system costs from US\$491.7 billion ( $\pm$  US\$116.0 billion) to US\$465.6 billion ( $\pm$  US\$110.7 billion) (Extended Data Fig. 2), this would result in a nearly three-quarters (73%) reduction in sediment supply (from  $53.8 \pm 3.4$  Mt per year to  $13.8 \pm 5.1$  Mt per year). The marginal sediment trapping of these high-impact dams (1.53 Mt per year per billion USD cost saving) is 30 times greater than that of low-impact hydropower dams. Therefore, developing low-impact dams could offer a better balance between cost savings and sediment supply. The smaller cost savings associated with low-impact dams stem from the fact that 11 of the 34 low-impact dams (12 GW) are located in the upper portion of the Mekong River in China, where electricity generation requires substantial investment in transmission infrastructure to reach downstream Mekong countries (Fig. 1b).

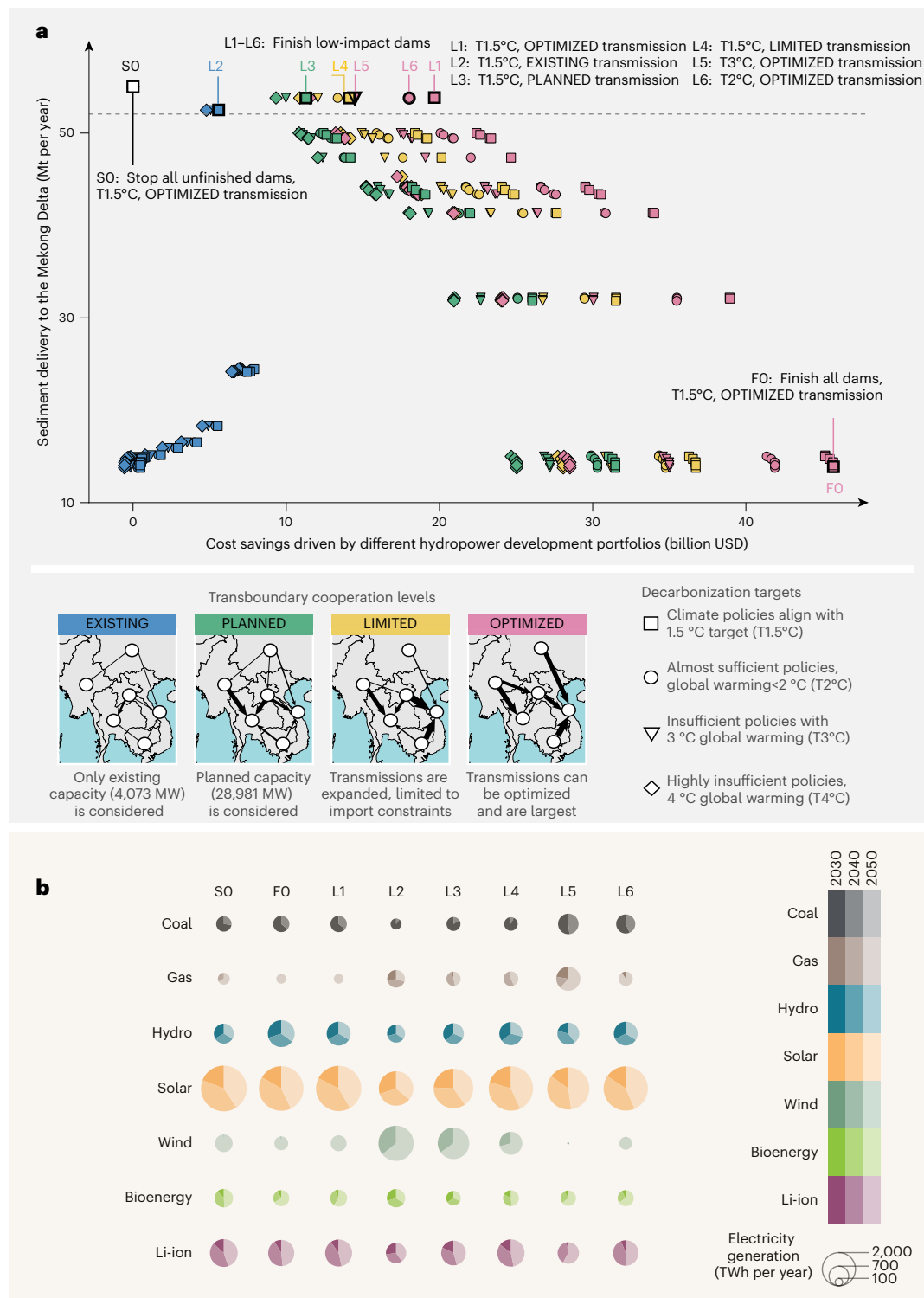
Among the 34 dams in the low-impact segment of the development sequence, 22 are located in river sections already disconnected from the delta by existing large dams, particularly in the upper Mekong in

China (for example, Xiaowan and Nuozhadu) and the 3S sub-basin (for example, Lower Se San 2) (Fig. 2b). Two of these dams on the upper Mekong mainstream (Ganlanba and Mengsong) are located downstream of large existing dams (such as Nuozhadu), thus having negligible impact on sediment delivery to the delta. Additionally, 3 of these 34 dams located on the lower Mekong mainstream, such as Stung Treng, have relatively low sediment-trapping rates, each with less than 11% trapping efficiency (see definition in Methods). Seven other low-impact dams are positioned in tributaries with relatively low sediment yields, receiving less than 0.2 Mt per year of sediment from the upstream catchment, such as Nam Ngiep 1. High-impact dams that trap substantial sediment include Luangprabang, Pakbeng, Paklay, Sangthong-Pakchom, Ban Kum and Sambor (Fig. 2c). Located along the mainstream of the MRB, these dams are expected to receive substantial sediment from upstream catchments, resulting in considerable sediment trapping<sup>13,24,43,44</sup>.

### Cost–sediment trade-offs under decarbonization and cooperation

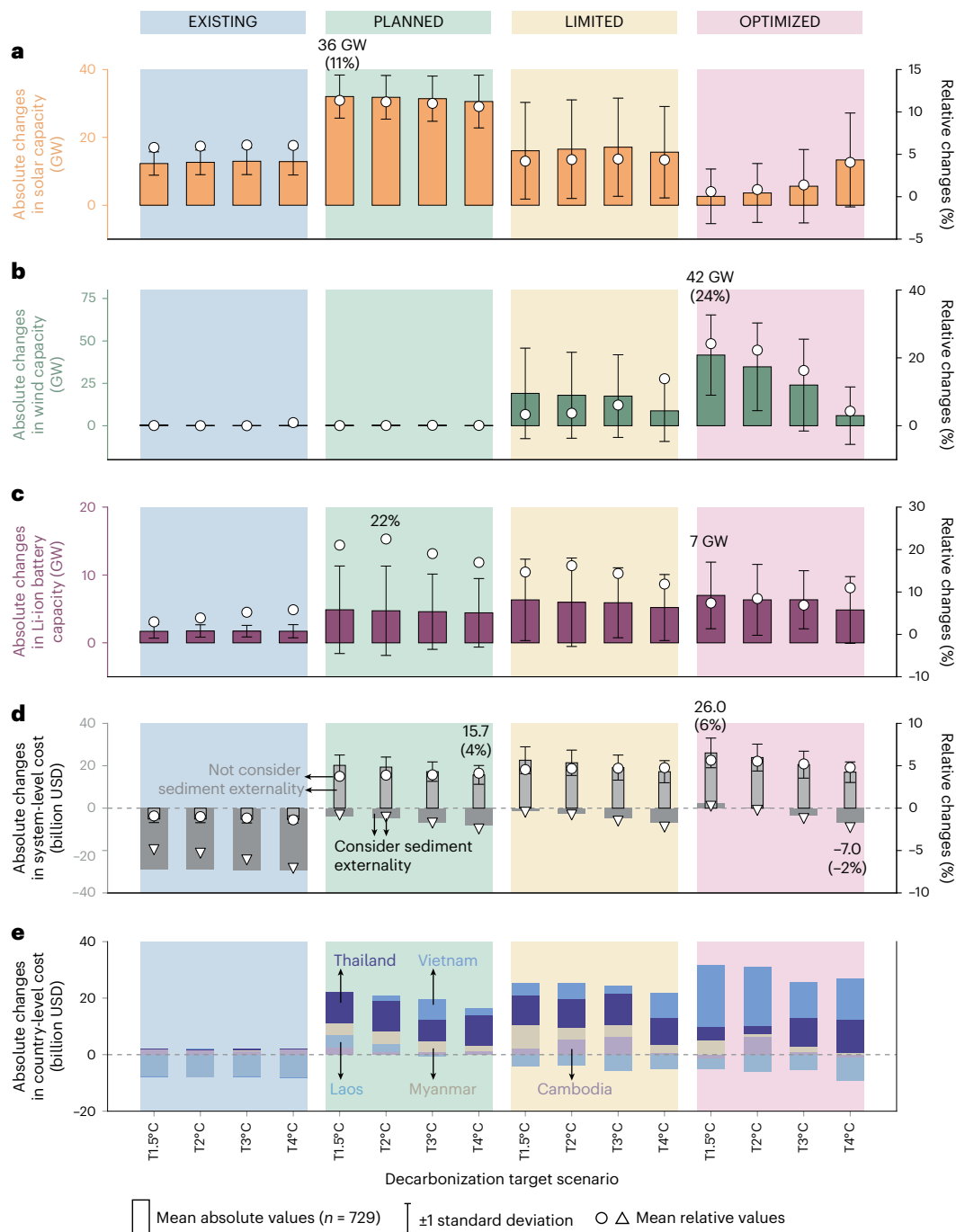
We demonstrate that an ambitious decarbonization target (T1.5°C) combined with enhanced regional cooperation in electricity transmission (OPTIMIZED) improves hydropower-driven cost savings, thereby better balancing the trade-off between energy system cost-optimality and preserving sediment supply (Fig. 3a). In addition to the most





**Fig. 3 | Sensitivities of sediment–cost trade-offs and energy capacity expansion pathways to decarbonization targets and electricity transmission capacities. a**, Markers from top to bottom denote the optimal sequences of dam construction under 16 plausible futures, each combining varying levels of decarbonization targets and degrees of transboundary cooperation. For clarity, we showcase only one low-impact hydropower portfolio along its optimal sequence. The dashed line separates low-impact vs high-impact hydropower plants with a threshold of 5% reduction in annual sediment supply compared to the status quo. Eight representative scenarios (S0, F0 and L1–L6) are highlighted for detailed analysis of electricity system pathways in **b**. Scenario S0 represents the status quo of the hydropower portfolio combined with T1.5°C decarbonization target and OPTIMIZED transmission capacity. Scenario F0

has the same decarbonization target and transmission capacity as S0, but for full hydropower development. Scenarios L1–L6 represent the development of only low-impact dams. L1 corresponds to the T1.5°C decarbonization target and OPTIMIZED transmission capacity. Scenarios L2, L3 and L4 reflect changes in transboundary electricity transmission restrictions based on L1, and L5 and L6 reflect changes in decarbonization targets based on L1. **b**, Temporal evolution of the electricity generation mixes from 2030 to 2050 for the eight highlighted scenarios. Country-specific generation and newly installed capacities in these eight scenarios can be found in Supplementary Figs. 5–9 and Extended Data Fig. 4, respectively. Uncertainty analysis related to Fig. 3 can be found in Extended Data Fig. 2 and Supplementary Figs. 1 and 2.



**Fig. 4 | Changes in energy system capacity mix and cost/benefits: low-impact versus full-development. a–c,** Increased solar capacity (a), wind capacity (b) and storage (Li-ion battery capacity; c) are required if we halt high-impact dams and maintain only low-impact dams. **d,** Changes in energy system costs over 2020–2050 and the ecosystem benefits from sediment supplied to the delta if high-impact dams are stopped. Substituting high-impact dams with additional VRE and storage technologies increases energy system costs across 12 scenarios, but these added costs are nearly offset when considering the benefits of sediment (triangles and dark grey bar). Bars represent the average

absolute differences compared to the full-development scenario, across  $n = 729$  uncertainty realizations, with error bars indicating  $\pm 1$  standard deviation. Open circles in **a–d** and triangles in **d** show average relative differences (percentage) across the same realizations. **e,** Country-level energy system cost changes over 2020–2050, considering only investment and O&M costs, excluding electricity import costs. Note that the percentage changes may be similar across different scenarios, even though the total changes vary considerably because the benchmarks are different.

optimistic energy expansion pathways discussed earlier, our analysis of 16 scenarios, characterized by 4 decarbonization targets (1.5 °C, 2 °C, 3 °C and 4 °C compatible) and 4 levels of transboundary transmission (EXISTING, PLANNED, LIMITED and OPTIMIZED), provides additional granularity and reveals similar cost–sediment trade-off curves (Fig. 3a). Specifically, given the same level of sediment was supplied

to the delta, under the T1.5 °C and OPTIMIZED transmission scenario (L1), hydropower-driven cost savings are maximized compared to other scenarios (for example, L2–L6).

Transmission expansion is critical for realizing the full potential of low-impact hydropower portfolios as it can maximize the hydropower–VRE complementarity due to the geographic mismatch

between hydropower resources and VRE/load centres. This underscores the need for holistic, basin-level planning rather than fragmented plant-by-plant approaches<sup>41</sup>. Without expanded transmission capacity (EXISTING transmission scenario, blue colour in Fig. 3a), the benefits of low-impact hydropower are limited, with cost savings less than US\$5.6 ± 1.6 billion over the planning horizon compared to other transmission scenarios (non-blue colours in Fig. 3a and Extended Data Fig. 2). Surprisingly, developing those 19 high-impact hydropower plants without additional transmission capacity can increase costs rather than reduce them, shifting the cost–sediment trade-off curves leftward, highlighting the constraints of current transmission infrastructure (Supplementary Table 1).

The existing and planned transmission capacity—only 3% and 23%, respectively, of the optimized 128 GW capacity in scenario L1—hinders power trade between hydropower-rich nations (Laos, Cambodia) and demand centres (Thailand, Vietnam), limiting the economic viability of hydropower investments. Additionally, the limited transmission capacity restricts electricity exports from solar-rich countries such as Myanmar and Laos to Thailand and Vietnam. Improvements are needed in transmission capacities between Laos and Vietnam, China and Vietnam, Cambodia and Vietnam, and Myanmar and Thailand to bridge the geographic mismatch between renewable supply and demand (Extended Data Fig. 3 and Supplementary Figs. 3 and 4).

Enhanced cross-country power trade facilitated by OPTIMIZED transmission (L1) enables more cost-effective transfer of hydropower, benefiting countries like Thailand and Vietnam to penetrate more VRE due to improved access of flexibility services provided by hydropower. Consequently, hydropower and solar generation increase by 79% (±22%) and 69% (±6%), respectively, in L1 compared to the EXISTING transmission scenario (L2), reducing the need for system-wide wind generation by 80% (±16%) (Fig. 3b and Supplementary Fig. 2), especially in Thailand and Vietnam (Supplementary Figs. 5 and 6). Therefore, without expanded transboundary transmission, the spatially uneven distribution of low-impact hydropower and VRE resources hinders their complementarity and limits the overall benefits.

The cost savings achieved through low-impact hydropower expansion are influenced not only by transmission constraints but also by decarbonization targets. Transitioning from a 3 °C-compatible to a more ambitious 1.5 °C-compatible policy, coupled with optimized cross-country transmissions, boosts cost savings from US\$14.5 billion (± US\$5.4 billion) (L5) to US\$19.6 billion (± US\$7.3 billion) (L1) when relying on low-impact dams alone (pink triangles versus pink squares in Fig. 3a and Extended Data Fig. 2). This is because the 3 °C-compatible future (L5) allows for greater reliance on fossil fuels like coal, gas and oil compared to the low-carbon future (L1). Consequently, thermal power generation in L5 surpasses that in L1 by 148% (±13%) (Fig. 3b and Supplementary Fig. 2). As fossil fuels are generally cheaper than VRE and storage technologies, VRE generation in L5 is 19% (±4%) lower than in L1 over the entire planning horizon.

### Sediment supply viability under VRE and storage deployment

Strategic hydropower planning that prioritizes low-impact projects necessitates a greater reliance on VRE and energy storage (Fig. 4a–c). This substitution strategy results in higher costs compared to full hydropower development, except in scenarios with existing transmission constraints (Fig. 4d). Specifically, halting high-impact dams requires substantial increases in solar (up to 36 GW or 11%), wind (up to 42 GW or 24%) and Li-ion battery (up to 7 GW or 22%) capacities to meet the total 2020–2050 electricity demand (Fig. 4a–c). The exact amounts of VRE and storage technologies required vary depending on transboundary cooperation levels and decarbonization targets (Fig. 3). Considering investment, operation and maintenance (O&M) costs, the alternative energy system mixes (featuring higher VRE and storage components) are on average US\$15.7–26.0 billion (4–6%) more expensive

than completing all high-impact hydropower projects in scenarios with PLANNED, LIMITED and OPTIMIZED transmission capacities (Fig. 4d).

Although substituting high-impact hydropower with VRE and storage incurs higher costs than full development, these additional costs are nearly offset by the environmental benefits of maintaining sediment delivery (Fig. 4d). Prioritizing low-impact hydropower and integrating VRE resources can preserve 98% of the current sediment supply to the Mekong Delta (Fig. 2a), a resource considered non-substitutable and crucial for maintaining the ecological balance and economic stability of the Mekong Delta<sup>16,25,45</sup>. Previous studies estimate that reducing sediment delivery to the Mekong Delta by 1 Mt leads to an economic loss of US\$20 ± 8 million per year<sup>30</sup>, primarily due to decreased rice production in Vietnam and Cambodia, as well as diminished coastal fishing activities in Vietnam. Based on these estimates<sup>30</sup>, our analysis suggests that replacing high-impact hydropower with VRE, which can avoid 40 Mt per year sediment loss (Fig. 2a), would prevent an economic loss of US\$24.0 billion (± US\$9.6 billion) ((20 ± 8) × 40 × 30/1,000) over 2020–2050 (see Supplementary Table 9 for estimating sediment's economic value). This avoided loss offsets added energy system costs in 10 out of 12 scenarios (Fig. 4d). When avoided losses from sediment are internalized in energy system planning, low-impact hydropower would have up to US\$7.0 billion cost advantage over the full development of hydropower. This indicates that although stopping high-impact hydropower leads to higher upfront costs, in the long run, it is still economically feasible.

The choice of dam development and VRE strategies also has equity implications on how costs and revenues should be distributed across the five MRB countries (Fig. 4e and Supplementary Figs. 10–14). Notably, Thailand bears the largest increases in energy system costs in most of scenarios, whereas the environmental benefits of sediment supply are predominantly felt by Vietnam.

## Discussions

Globally, hydropower expansion in developing regions, such as the MRB, has raised concerns due to its negative eco-environmental consequences, notably reduced sediment delivery to downstream deltas<sup>15,18</sup>. This sediment supply is vital for mitigating delta land loss<sup>46</sup>, providing nutrients for aquatic and agricultural production<sup>47</sup> and maintaining ecosystem services<sup>18</sup>. Prior studies have quantified the lost opportunities resulting from historical hydropower development and identified remaining opportunities for improved trade-offs between sediment and hydropower generation<sup>24,33,34,48</sup>. However, hydropower development cannot be assessed in isolation by focusing solely on its generation. This is because hydropower also offers various non-generation ancillary energy services for a future grid with more VRE<sup>41</sup>. Rather, hydropower's role in mitigating the trade-offs between climate mitigation and adaptation should be evaluated within a broader energy system context. This energy systems context necessitates co-optimizing hydropower with other renewable technologies and transmission infrastructure to balance low-energy system costs, maintain sediment supply, meet future electricity demands and achieve climate targets<sup>49</sup>. Our study expands the scope beyond simple hydropower–sediment trade-offs to a more comprehensive evaluation in two key domains. First, we assess the techno-economic feasibility of different hydropower planning strategies from a power grid expansion perspective. Second, we provide a holistic perspective on costs, including costs from foregone ecosystem services, going beyond the often-used energy system costs.

In addition to the basin-level strategic planning, our coupled water–sediment–energy modelling framework (Extended Data Fig. 1) allows for plant-by-plant analysis to quantify the individual contributions of each hydropower plant to the system-level cost and sediment trapping (Extended Data Fig. 5). Among the 53 ongoing and planned plants, 3 low-impact hydropower plants—Stung Treng (Cambodia), Phou Ngoy (Laos) and Sanakham (Laos)—contribute US\$3.7 billion (8%), US\$2.8 billion (6%) and US\$2.2 billion (5%), respectively, to

system-level cost savings over 2020–2050. In contrast, six high-impact hydropower plants, including Sambor (Cambodia) and five in Laos (Ban Kum, Paklay, Luangprabang, Sangthong-Pakchom and Pakbeng), contribute US\$6.2 billion (13%), US\$4.9 billion (10%), US\$4.8 billion (10%), US\$3.4 billion (7%), US\$3.4 billion (7%) and US\$1.3 billion (3%), respectively, to system-level cost savings over 2020–2050 (Extended Data Fig. 5). It is important to note that in 2020, Cambodia announced a ten-year moratorium on mainstream Mekong dams, including the Sambor and Stung Treng projects, due to environmental concerns<sup>50</sup>. Our findings align with this policy direction in the case of Sambor, which is identified as a high-impact dam in terms of sediment trapping. However, Stung Treng, classified as low-impact in terms of sediment trapping, may still pose threats to other ecological functions, such as fish migration<sup>51</sup>. This underscores the need for multicriteria environmental assessments, including efforts to quantify dam impacts on, for example, fisheries, when evaluating future dam development.

Our findings underscore the importance of building a regional power grid<sup>36,52</sup> for achieving a more favourable balance between sediment supply and power system costs (Fig. 3a). Enhanced cross-border electricity cooperation not only reduces total system costs but also supports low-impact hydropower projects by facilitating flexible power transfers across countries. However, it is essential to recognize that different countries benefit differently from the sediment–energy co-optimization framework, which can challenge regional cooperation. For example, Vietnam benefits most from maintaining sediment supply<sup>30</sup>, given sediment's critical role in stabilizing the Mekong Delta and rice production, which contributes to 50% of the country's total rice yield. However, the elevated energy system costs are shared among the five Mekong countries, especially Thailand (Fig. 4e). These disparities in benefits and burdens could impact transboundary cooperation dynamics. Moreover, although the economic viability of Mekong decarbonization appears promising, geopolitical factors could present additional challenges, particularly when countries face parallel decarbonization pressure or want to prioritize domestic energy security. Thus, better policy incentives are needed to enhance cooperation through shared benefits, information and transboundary electricity trade.

Strengthened regional cooperation would be critical to address the above uneven spatial distribution in environmental benefits and energy system costs. For example, establishing benefit-sharing mechanisms could be one viable option to align national incentives. Such mechanisms may include financial compensation, ecosystem service payments or premium electricity pricing schemes to encourage upstream countries to forgo high-impact hydropower development. For example, Vietnam could offer favourable power purchase agreements or side payments to countries that prioritize sediment preservation over hydropower expansion<sup>53</sup>. Moreover, coordinated transmission expansion could offer a practical pathway to reduce overall system costs and improve grid flexibility, thereby expanding the pool of benefits available for redistribution. Together, these measures can support a more equitable and politically feasible framework for sediment–energy planning in the Mekong.

Although our study considers policies compatible with 4 decarbonization targets (1.5 °C, 2 °C, 3 °C and 4 °C increase in global temperature), our representation of hydrology is based on current climate conditions. Meanwhile, our analysis does not consider future climate extremes like droughts, which could considerably affect water availability for hydropower generation. Additionally, climate change will alter sediment dynamics<sup>26</sup>. Thus, prioritizing low-impact hydropower and developing VRE can mitigate reliance on water-dependent high-impact hydropower, offering the co-benefits of maintaining sediment supply and enhancing power grid resilience against climate extremes.

It should be noted that dams are often built for multiple purposes, such as water supply and flood protection, that cannot be substituted by VREs. Although some dams in the Mekong provide such hydrologic services, nearly all big dams in the basin are designed for hydropower,

according to ref. 24 and global dam data<sup>54</sup>. Moreover, our framework currently centres sediment delivery as the principal environmental criterion. Expanding the environmental scope remains an important direction, with promising avenues including fish migration<sup>55</sup>, river fragmentation<sup>38</sup> and flood pulse connectivity metrics<sup>56</sup>. Thus, future studies can extend the model to incorporate additional reservoir objectives beyond energy and sediment.

In conclusion, our framework enables explicit trade-offs between river ecosystem services and energy system costs and feasibility. Particularly when expanded to cover a broader perspective on river ecosystem services and additional objectives of water infrastructure, our approach can be used to develop least-impact development pathways and cost–benefit sharing mechanisms for many river basins with pressures for water infrastructure development.

## Methods

### Overview of the multisectoral water–sediment–energy planning framework

We developed an integrated water–sediment–energy planning framework (Extended Data Fig. 1) to systematically quantify the economic costs and environmental impacts (focusing on sediment supply) of hydropower expansion on energy system pathways in the MRB. Our modelling framework couples a semidistributed hydrological model, a modular energy capacity expansion model (with more realistic representations of reservoir hydropower operations) and a physics-based sediment routing model. By employing a multi-objective optimization model, we identified environmentally friendly dam development sequences that enable a low-cost clean energy transition. We then investigated how strategic, system-level planning can minimize the trade-offs between energy system costs and sediment supply under 16 diverse decarbonization and transboundary cooperation scenarios.

We used the Soil and Water Assessment Tool (SWAT) hydrological model<sup>57</sup> to simulate historical (1962–2005) daily streamflow across the MRB. These streamflow simulations serve as the key input for estimating hydropower generation. SWAT also simulates natural sediment transport along the river network, including sub-basin-level estimates of sediment yield and conveyance loss. These data are key inputs to the sediment routing model for estimating how much sediment can be delivered to the Mekong Delta<sup>15,18</sup>.

Previous studies indicate that hydropower expansion in the MRB affects both the energy system costs<sup>38</sup> and the amount of sediment that can be transported to the downstream delta<sup>16,48</sup>. However, these studies often treat sediment routing and energy system expansion in isolation, failing to fully capture the crucial trade-offs and feedback between energy system expansion costs and environmental damage caused by sediment trapping. Such modelling approaches may overlook potential compromise solutions. Developing a sediment–energy co-optimization model is therefore crucial to systematically examine the trade-offs between energy system costs and sediment supply. In this study, we directly coupled a sediment routing module into an energy capacity expansion model. This allows us to better characterize the two-way feedback between sediment supply and energy systems, linked by hydropower expansion. The primary objectives of this sediment–energy co-optimization are (1) to minimize energy system costs and (2) to maximize sediment supply to the Mekong Delta. To efficiently obtain the Pareto frontier of these two objectives, we transformed the dual-objective problem into a single-objective problem using the epsilon-constrained method<sup>58</sup>. Because our model includes additional dam investment decisions (whether to build or not, binary variables), the optimization becomes a mixed-integer linear programming problem rather than a linear programming problem.

Solving the above dual-objective optimization allows us to identify the cost-optimal dam portfolios that balance the trade-off between energy system costs and sediment supply. Although identifying these Pareto-optimal dam portfolios is important, additional consideration



of the optimal building sequence (that is, project-by-project development) is also crucial for system-level strategic dam planning in a more adaptive way. This ensures that in case there is a need to halt hydropower expansion due to environmental objections, the resultant dam portfolio still maintains favourable trade-offs. Given the high-dimensional decision space and the computational challenges of directly determining dam investment priorities while meeting unknown preferences across multiple objectives, here we post-processed the Pareto-optimal dam portfolios to identify the optimal sequencing of future dam construction, following the approach proposed in ref. 24. This post-processing analysis produced the final Pareto-optimal trade-offs between system costs and sediment supply throughout this paper (Figs. 2 and 3).

### Hydrological model

We used the SWAT hydrological model to obtain the spatial-temporal continuous streamflow and sediment yield information at the sub-basin level in the MRB. SWAT is a physically based semi-distributed hydrological model widely used for water resources and sediment management due to its ability to well capture the streamflow-sediment interactions in large watersheds<sup>27,57</sup>. The key model input data for SWAT include meteorological forcings (for example, precipitation, solar radiation), soil properties (for example, soil bulk density, organic matter content), elevation and land-use information (see Supplementary Table 2 for details). More details on the SWAT setup can be found in our previous study<sup>27</sup>.

We ran the SWAT model from 1960 to 2005, discarding the initial two years (1960 and 1961) as model spin-up. Calibration and validation of SWAT-simulated streamflow and sediment were conducted over different periods, depending on the availability of daily measurements at ten gauges provided by the Mekong River Commission (MRC) (see Supplementary Figs. 15–17 for detailed calibration results and Supplementary Table 3 for calibrated parameters associated with streamflow and sediment routing). Specifically, SWAT-simulated streamflow was calibrated over 1962–1984, with a validation period from 1985 to 1999. For sediment, calibration was performed for 1962–1980, and validation covered 1981–1990.

Our calibrated SWAT model successfully replicated daily streamflow dynamics across the river network under natural conditions, excluding the operational effects of dams. These simulated flows served as inflow inputs to individual reservoirs in our energy capacity expansion model (Pathways for Renewable Energy Planning coupling Short-term Hydropower Operation (PREP-SHOT))<sup>10</sup> and were extracted based on each plant's upstream catchment area (see details in Supplementary Methods 1).

### Sediment–energy co-optimization model

As sediment is a critical environmental constraint in hydropower planning, it is important to jointly optimize energy production/expansion and sediment supply rather than treating them separately. To achieve this, we tightly coupled the energy capacity expansion model PREP-SHOT<sup>10</sup> with the network-scale sediment routing model CASCADE (CAatchment Sediment Connectivity And Delivery)<sup>24,59</sup>. This hard coupling strategy allows us to more accurately capture the trade-offs between energy system cost savings and sediment supply reduction for a given dam portfolio.

PREP-SHOT is a transparent, modular and open-source energy capacity expansion model designed to optimize the expansion of energy system capacity along with the hourly dispatch of generation, transmission and storage. Unlike other energy expansion models<sup>35,36,38,39,56</sup>, a unique feature of PREP-SHOT is its advanced representation of short-term hydropower flexibility in long-term energy system planning. Specifically, PREP-SHOT considers both plant-level hydropower dynamics and the system-level network topology of hydropower dams within the river basin. This results in a more accurate

reflection of the multiscale dynamic feedback between hydropower operation and energy system expansion. Furthermore, it enables a more realistic simulation of the magnitude and spatial-temporal variability of hydropower output, especially in regions like the MRB with a large number of cascade hydropower stations<sup>10</sup>.

In this study, PREP-SHOT was configured at the country level, focusing on five Mekong countries—Thailand, Cambodia, Laos, Vietnam and Myanmar—as individual planning units for energy system development (Fig. 1). To account for hydropower from the upper Mekong (Lancang) in southwestern China, we modelled this generation as an exogenous electricity export to downstream countries. We did not explicitly model southern China's internal power system—including coal and gas generation—because doing so would have required simulating the full Chinese power grid, which spans multiple provinces and operates under a distinct national planning framework. This simplification preserved the study's focus on Mekong-region dynamics while still acknowledging southern China's role as a regional energy exporter<sup>53</sup>. Our analysis included 124 large hydropower dams within the MRB, primarily constructed for power generation, based on the dataset by ref. 24. Although our study focused on the MRB, we incorporated 11 major existing hydropower plants located outside the MRB, following the dataset provided by ref. 60. We ran PREP-SHOT at an hourly temporal resolution for 12 representative days in four selected planning years (2020, 2030, 2040 and 2050), with one representative day chosen for each month to account for strong inflow seasonality. Further details of PREP-SHOT and its configuration in our study can be found in Supplementary Methods 1 and ref. 10.

We used the CASCADE model to simulate the suspended sediment balance at the sub-basin level across the entire MRB and assess sediment delivery to the Mekong Delta. Our analysis focused on suspended sediment, excluding bedload, to align with the sediment measurements used for SWAT calibration, as provided by the MRC<sup>27</sup>. This may lead to a conservative estimate of sediment trapping because coarse-grained bedload sediment is trapped even more efficiently by reservoirs<sup>24,61</sup>. To quantify sediment dynamics throughout the river network, CASCADE conceptualizes the river network as a directed graph and calculates sediment supply based on two key components: the natural sediment transport component and sediment trapping by dams. The natural sediment transport component relies on outputs from the SWAT model, which provides sediment yield from hillslopes and sediment transport losses along natural river segments. Sediment trapping in reservoirs was calculated using the Brune method<sup>62</sup>, an empirical approach commonly applied in data-scarce basins where physics-based hydrodynamic models are not feasible. This approach calculates sediment trapping efficiency in a reservoir based on two parameters: the mean reservoir storage volume and the total annual inflow. Using its graph-based calculation scheme, CASCADE routes sediment from individual sources through the downstream network to the basin outlet, simultaneously calculating cumulative sediment trapping at all dams. This provides a spatially distributed estimate of sediment flux in each reach and sediment supply to the downstream delta.

The dual-objective optimization requires key inputs related to the energy system and sediment routing calculations. For the energy system, inputs include information on existing power infrastructure (for example, power plants, transmission lines and storage technologies), hourly capacity factors for renewable technologies in each country, cost parameters (for example, discount rate, investment cost, fixed and variable O&M costs, fuel cost), the lifetime of power technologies and transmission lines, ramping rates, lower and upper bounds of country-level installed capacities of each technology, carbon emission factors of thermal power plants, electricity transmission topology and efficiency, storage technology parameters (for example, discharging/charging efficiency and initial storage level) and projected electricity demand for each country over the planning horizon. To accurately represent plant-level hydropower generation, daily streamflow across

the river network is also required. For the sediment routing component, we used SWAT-simulated sub-basin level sediment yield and natural sediment conveyance loss to estimate sediment supply along the river network. More details on this sediment–energy co-optimization framework can be found in Extended Data Tables 1 and 2, Supplementary Tables 4–6 and Supplementary Methods 2 and 3.

Major outputs, or decision variables, of this co-optimization model include the following: country-level capacity of newly constructed technologies per modelled year, the capacity of newly built transmission lines per modelled year for paired neighbouring countries, country-level hourly generation of each technology per modelled year, hourly transmitted power per modelled year for paired neighbouring countries and hourly discharge and storage dynamics of each hydropower plant. Binary decision variables for future planned hydropower plants determine the dam portfolio and, consequently, the amount of sediment that could be transported to the Mekong Delta. It should be noted that our model does not explicitly incorporate reserve margin, which may underestimate the firm capacity required to ensure system reliability. Further details on the co-optimization outputs can be found in Extended Data Table 2.

The two major objectives are to minimize the total energy system costs ( $\text{cost}^{\text{total}}$ ) and maximize sediment supply to the Mekong Delta (sediment<sup>MD</sup>):

$$\begin{aligned} \text{obj1 : } \min \text{cost}^{\text{total}} \\ = \text{cost}^{\text{fuel}} + \text{cost}^{\text{var}_{\text{tech}}} + \text{cost}^{\text{var}_{\text{line}}} + \text{cost}^{\text{fix}_{\text{tech}}} + \text{cost}^{\text{fix}_{\text{line}}} + \text{cost}^{\text{inv}_{\text{tech}}} + \text{cost}^{\text{inv}_{\text{line}}} \quad (1) \\ \text{obj2 : } \max \text{sediment}^{\text{MD}} = \sum_{\xi \in \Omega} \text{sediment}^{\xi}_{\text{yield}} - \sum_{\xi \in \Omega} \text{sediment}^{\xi}_{\text{loss}} \end{aligned}$$

where  $\text{cost}^{\text{fuel}}$ ,  $\text{cost}^{\text{var}_{\text{tech}}}$ ,  $\text{cost}^{\text{var}_{\text{line}}}$ ,  $\text{cost}^{\text{fix}_{\text{tech}}}$ ,  $\text{cost}^{\text{fix}_{\text{line}}}$ ,  $\text{cost}^{\text{inv}_{\text{tech}}}$  and  $\text{cost}^{\text{inv}_{\text{line}}}$  (units: USD) are the system-wide fuel cost, variable O&M cost of electricity generation technologies, variable O&M cost of transmission lines, fixed O&M cost of electricity generation technologies, fixed O&M cost of transmission lines, investment cost of electricity generation technologies and investment cost of transmission lines, respectively (see Extended Data Table 1 for details).  $\text{sediment}^{\xi}_{\text{yield}}$  (units: Mt per year) is the sediment yield in sub-basin  $\xi$ , which is the total amount of sediment particles detached from the landscape to rivers.  $\Omega$  is the set of sub-basins. In total, 552 sub-basins are delineated in the SWAT model. Specifically, each sub-basin corresponds to a river reach.  $\text{sediment}^{\xi}_{\text{loss}}$  (units: Mt per year) is the conveyance loss in river reach of sub-basin  $\xi$ . For river reaches without any dams,  $\text{sediment}^{\xi}_{\text{loss}}$  can be estimated as the sediment deposition in natural river networks, which is a function of sediment transport capacity. For river reaches with dams,  $\text{sediment}^{\xi}_{\text{loss}}$  refers to the sediment volume trapped by the dam.

Major constraints considered in PREP-SHOT include carbon emission limits, power balance requirements, transmission capacity limits, power output variation constraints, power output upper limits, technology lifetime, water balance constraints, energy storage limits, reservoir outflow constraints and reservoir storage constraints. Because our co-optimization explicitly incorporated sediment processes, additional sediment balance constraints needed to be considered:

$$\text{sediment}^{\xi}_{\text{loss}} = \text{sediment}^{\xi}_{\text{in}} - \text{sediment}^{\xi}_{\text{out}} \quad (2)$$

$$\text{sediment}^{\xi}_{\text{in}} = \sum_{\lambda \in \Omega^{\xi}} \text{sediment}^{\lambda}_{\text{out}} + \text{sediment}^{\xi}_{\text{yield}} \quad (3)$$

where  $\text{sediment}^{\xi}_{\text{in}}$  (units: Mt per year) is the total amount of sediment transported into the river reach of sub-basin  $\xi$ , which is the sum of the sediment yield in sub-basin  $\xi$  ( $\text{sediment}^{\xi}_{\text{yield}}$ ) and the sediment flux from all upstream sediment sources ( $\sum_{\lambda \in \Omega^{\xi}} \text{sediment}^{\lambda}_{\text{out}}$ ).  $\Omega^{\xi}$  is the set of sub-basins that are upstream of and connected to sub-basin  $\xi$ .  $\lambda$  is a

specified sub-basin that belongs to  $\Omega^{\xi}$ .  $\text{sediment}^{\xi}_{\text{out}}$  (units: Mt per year) is the sediment flux flowing out of sub-basin  $\xi$  and is estimated as

$$\begin{cases} \text{sediment}^{\xi}_{\text{out}} = \text{sediment}^{\xi}_{\text{in}} \times (1 - \text{rate}^d_{\text{trapping}}) & \text{if dam } d \text{ exists in sub-basin } \xi \\ \text{sediment}^{\xi}_{\text{out}} = \text{sediment}^{\xi}_{\text{in}} \times (1 - \text{rate}^{\xi}_{\text{deposition}}) & \text{if sub-basin } \xi \text{ is free of dams} \end{cases} \quad (4)$$

where  $\text{rate}^{\xi}_{\text{deposition}}$  (units: %) is the sediment deposition rate in river reach  $\xi$  under natural conditions (without dams), defined as 1.0 minus the sediment conveyance rate. The conveyance rate is estimated by dividing the multiyear averaged amount of sediment transported out of reach  $\xi$  by the total amount of sediment transported into reach  $\xi$ , both obtained from the SWAT model simulations.  $\text{rate}^d_{\text{trapping}}$  (units: %) is the sediment trapping rate in dam  $d$  and also located in river reach  $\xi$  based on the widely applied Brune method<sup>62</sup>:

$$\text{rate}^d_{\text{trapping}} = 1 - \frac{0.05}{\sqrt{Cl^d}} \quad (5)$$

$$Cl^d = \frac{V^d}{Q^d} \quad (6)$$

where  $Cl^d$  (units: year) is the ratio of mean operational reservoir storage volume  $V^d$  (units: km<sup>3</sup>) to total annual inflow  $Q^d$  (units: km<sup>3</sup> per year). Based on equations (2)–(6), CASCADE can estimate the final amount of sediment that is supplied to the Mekong Delta accounting for conveyance losses from natural deposition and sediment trapping by dams.

It should be noted that, in our optimization model, estimation of sediment<sup>MD</sup> is contingent upon the hydropower portfolio, which depends on whether the 53 ongoing and planned dams in the MRB will be constructed or halted in the future. To represent this investment decision, we introduced a binary decision variable  $\chi^d$ , with 1 indicating that dam  $d$  (where  $d$  belongs to the set of all ongoing and planned dams) is constructed and 0 indicating that it is stopped. Incorporating sediment flux modelling transforms the previous linear programming model into a mixed-integer nonlinear programming model, which is more challenging to solve. In this study, we applied the big-M method<sup>63</sup> to convert the nonlinear sediment balance constraint outlined in equation (4) into a linear constraint (equations (7)–(10)):

$$\frac{\text{sediment}^{\xi}_{\text{out}} - \text{sediment}^{\xi}_{\text{in}} \times (1 - \text{rate}^{\xi}_{\text{deposition}})}{\text{rate}^{\xi}_{\text{deposition}} - \text{rate}^d_{\text{trapping}}} \leq \text{sediment}^{\xi}_{\text{in}} + (1 - \chi^d) \times M \quad (7)$$

$$\frac{\text{sediment}^{\xi}_{\text{out}} - \text{sediment}^{\xi}_{\text{in}} \times (1 - \text{rate}^{\xi}_{\text{deposition}})}{\text{rate}^{\xi}_{\text{deposition}} - \text{rate}^d_{\text{trapping}}} \geq \text{sediment}^{\xi}_{\text{in}} - (1 - \chi^d) \times M \quad (8)$$

$$\frac{\text{sediment}^{\xi}_{\text{out}} - \text{sediment}^{\xi}_{\text{in}} \times (1 - \text{rate}^{\xi}_{\text{deposition}})}{\text{rate}^{\xi}_{\text{deposition}} - \text{rate}^d_{\text{trapping}}} \leq \chi^d \times M \quad (9)$$

$$\frac{\text{sediment}^{\xi}_{\text{out}} - \text{sediment}^{\xi}_{\text{in}} \times (1 - \text{rate}^{\xi}_{\text{deposition}})}{\text{rate}^{\xi}_{\text{deposition}} - \text{rate}^d_{\text{trapping}}} \geq -\chi^d \times M \quad (10)$$

where  $M$  is a user-defined large number, in this case 10,000.

A key innovation of our modelling approach lies in the co-optimization of the coupled sediment–energy system, which involves both continuous variables (for example, hydropower generation from existing and planned hydropower plants) and binary decision variables

(whether to build planned hydropower plants). Directly solving a full-year 8,760-hour power balance requires optimizing hundreds of millions of decision variables (for example, hourly dispatch for each technology in each country and hourly generation outflows for each hydropower plant), which is computationally intractable. To overcome this challenge, we propose a computationally efficient strategy with three dimensionality-reduction techniques (see details in Supplementary Methods 4).

### Trade-off analysis based on Pareto-optimal dam sequences

In each analysed scenario (see Table 1 for details), we performed 200 iterations of the proposed sediment–energy co-optimization using the epsilon-constrained method<sup>58</sup> to address the dual-objective optimization problem. This process yielded a Pareto frontier containing 200 dam portfolios that balanced the trade-off between energy system costs and sediment supply. Although the dam portfolios along the Pareto frontier exhibit a vast array of possible spatial configurations of dam sites, they do not necessarily form a practical sequence for hydropower expansion. To derive the optimal construction sequence for all ongoing and planned dams (53 in total), we employed a sequencing algorithm<sup>24</sup>. This adaptive optimal sequence allows for the possibility of halting hydropower development if hydropower demand is lower than projected or if alternative renewables can replace hydropower, while still achieving favourable trade-offs between energy and sediment systems<sup>24</sup>. To identify the optimal sequence, we calculated the probability of hydropower plant  $i$  appearing in the Pareto-optimal solutions, denoted as  $\text{Prob}_i$ :

$$\text{Prob}_i = \frac{\sum_{n=1}^{N_{\text{PO}}} \rho_{i,n}}{N_{\text{PO}}} \quad (11)$$

where  $N_{\text{PO}}$  is the number of Pareto-optimal solutions;  $\rho_{i,n}$  is a binary indicator with 1 indicating that the  $i$ th dam appears in the  $n$ th Pareto-optimal solution and vice versa. Subsequently, we ranked all the dams according to  $\text{Prob}_i$ , resulting in a sequence that represented the optimal order of constructing these hydropower plants. Our results (Supplementary Fig. 22) demonstrate that the trade-offs along an optimal sequence are closer to the trade-offs created by individual portfolios along the original Pareto frontier.

Following the optimal construction sequence, we derived a series of dam portfolios, each representing step-by-step development of hydropower projects. We then recalculated sediment supplies to the Mekong Delta and re-optimized energy system pathways based on these dam portfolios. We did so because these portfolios may not all appear on the original Pareto-optimal frontier. In this case, we ran CASCADE and PREP-SHOT separately because the dam portfolios were predetermined, eliminating the feedback between sediment supply and hydropower expansion. This post-processing approach produced Pareto-optimal trade-offs between system costs and sediment supply along the optimal sequence, which are presented throughout this paper (Figs. 2 and 3).

### Experiment and scenario design

We designed 16 scenarios to examine how decarbonization targets and transboundary electricity transmission policies affect sediment–energy trade-offs. These scenarios encompassed four distinct decarbonization pathways (reflecting decarbonization efforts) and four electricity transboundary transmission limitations (reflecting transboundary cooperation effects), as detailed in Table 1.

Decarbonization targets (carbon emission limits) served as proxies for the stringency of constraints imposed on fossil-fuel-based electricity generation, thereby altering the role of hydropower within the energy system. We defined four decarbonization scenarios based on the CAT<sup>42</sup>: 1.5 °C-compatible (T1.5°C), 2 °C-compatible (T2°C), 3 °C-compatible (T3°C) and 4 °C-compatible (T4°C). As an independent

scientific initiative, CAT evaluates national climate pledges relative to the Paris Agreement's objectives and provides policy-relevant emissions constraints for each scenario, assuming all six countries implement nationally determined contributions with similar ambition levels (see details in Table 1). The CAT dataset was used to impose country-level upper bounds on carbon emissions for the period 2020–2050 (detailed in Supplementary Method 3). The selected temperature thresholds (1.5 °C, 2 °C, 3 °C and 4 °C) are widely used in climate mitigation studies and reflect different levels of policy ambition. The T1.5°C and T2°C scenarios align with the Paris Agreement targets, representing ambitious and moderate decarbonization efforts, respectively. In contrast, the T3°C and T4°C scenarios reflect weaker policy actions, where current commitments fall short of achieving necessary emission reductions.

Given that the cross-country cooperation in electricity transmission is already underway in the MRB and is expected to play a more pivotal role in future sustainable development<sup>38</sup> (Fig. 1b), accounting for uncertainties in cooperation levels is essential for optimizing renewable energy benefits while managing hydropower development's environmental impacts. Thus, we designed four transboundary transmission scenarios (EXISTING, PLANNED, LIMITED and OPTIMIZED; Table 1) to reflect the current state and potential developments in the regional power pool in the Mekong. The first two scenarios focus on existing and planned transmission capacity<sup>64</sup>. To delve deeper into the impact of enhanced coordination among the six Mekong countries, we introduced two compelling scenarios. The LIMITED transmission scenario assumes that transboundary electricity transmission among the lower Mekong countries can surpass the planned capacity to boost power trade. However, to address national energy security concerns, each country's imports are limited to one-third of its total electricity demand, as documented in refs. 65,66. Notably, we only modelled China's hydropower generation in the Lancang River and did not account for its domestic electricity demand. Given that hydropower generation in Southwest China (Yunnan and Tibet provinces) serves as an important source to meet domestic electricity demand in other parts of China, we imposed a restriction that China's electricity exports should not exceed one-third of its hydropower generation<sup>67</sup> in the Lancang River in the LIMITED transmission scenario. The OPTIMIZED transmission scenario allows for the co-optimization of transmission capacity with generation and storage capacity investments and operations<sup>36</sup>. For the EXISTING and PLANNED transmission scenarios, transboundary interconnections were used as input variables in the co-optimization model. In contrast, for the LIMITED and OPTIMIZED transmission scenarios, these interconnections were treated as decision variables that must be optimized within the specified upper limits. These diverse scenarios offered a more comprehensive perspective, enabling us to better understand the intricate balance between regional cooperation and national energy security, driving forward our quest for sustainable and cost-effective energy development strategies in this transboundary river basin.

### Reporting summary

Further information on research design is available in the Nature Portfolio Reporting Summary linked to this article.

### Data availability

Decarbonization target data are available via CAT (<https://climateactiontracker.org/>). Solar and wind capacity factor data are accessible through [Renewables.ninja](https://renewables.ninja). Dam and reservoir characteristics are available in the supplementary material of refs. 24,60. Public datasets used to drive SWAT model simulations are available via SRTM 90m Digital Elevation Database v4.1, CGIAR-CSI (<https://csidotinfo.wordpress.com/data/srtm-90m-digital-elevation-database-v4-1/>), ISLSCP IIIGBP DISCover and SiB Land Cover, 1992–1993 (<https://doi.org/10.3334/ORNLDAAC/930>; land-use map) and Harmonized World Soil Database



v1.2 (<https://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/>; soil map). Measurements of streamflow and suspended sediment concentration in the MRB are obtained from the MRC (<https://portal.mrcmekong.org/home>). All other data used in the optimization are provided in the Supplementary Information and are cited from publicly available sources.

## Code availability

The energy expansion model PREP-SHOT is available under the GNU General Public License version 3 (GPLv3) and can be downloaded from the GitHub repository (<https://github.com/PREP-NexT/PREP-SHOT>) of the Pathways for REsilient Planning of water-energy-food Nexus Transformation (PREP-NexT) Lab. SWAT and CASCADE are open-source tools and are available via <https://swat.tamu.edu/> and <https://cascade.deib.polimi.it>, respectively. Codes and input data for the multisectoral water–sediment–energy planning framework are provided in the following GitHub repository: <https://github.com/PREP-NexT/Mekong-Energy-Sediment>.

## References

- Renewables 2023 (IEA, 2024); <https://www.iea.org/reports/renewables-2023>
- Ritchie, H. & Rosado, P. Electricity mix. *Our World in Data* (2020).
- Electricity System Flexibility by Source, 2020 and 2030 in the Net Zero Scenario (IEA, 2021); <https://www.iea.org/data-and-statistics/charts/electricity-system-flexibility-by-source-2020-and-2030-in-the-net-zero-scenario>
- Net Zero by 2050 - A Roadmap for the Global Energy Sector (IEA, 2021).
- Global Renewables Outlook: Energy Transformation 2050 (International Renewable Energy Agency, 2020).
- Wasti, A. et al. Climate change and the hydropower sector: a global review. *WIREs Clim. Change* **13**, e757 (2022).
- Schmitt, R. J. P. & Rosa, L. Dams for hydropower and irrigation: trends, challenges, and alternatives. *Renew. Sustain. Energy Rev.* **199**, 114439 (2024).
- Net Zero Roadmap: A Global Pathway to Keep the 1.5 °C Goal in Reach (IEA, 2023); <https://www.iea.org/reports/net-zero-roadmap-a-global-pathway-to-keep-the-15-0c-goal-in-reach>
- World Energy Transitions Outlook 2023: 1.5 °C Pathway (International Renewable Energy Agency, 2023).
- Liu, Z. & He, X. Balancing-oriented hydropower operation makes the clean energy transition more affordable and simultaneously boosts water security. *Nat. Water* **1**, 778–789 (2023).
- Sterl, S. et al. Smart renewable electricity portfolios in West Africa. *Nat. Sustain* **3**, 710–719 (2020).
- Sterl, S., Fadly, D., Liersch, S., Koch, H. & Thiery, W. Linking solar and wind power in eastern Africa with operation of the Grand Ethiopian Renaissance Dam. *Nat. Energy* **6**, 407–418 (2021).
- Wild, T. B., Reed, P. M., Loucks, D. P., Mallen-Cooper, M. & Jensen, E. D. Balancing hydropower development and ecological impacts in the Mekong: tradeoffs for Sambor Mega Dam. *J. Water Resour. Plan. Manag.* **145**, 05018019 (2019).
- Pokhrel, Y. et al. A review of the integrated effects of changing climate, land use, and dams on Mekong River Hydrology. *Water* **10**, 266 (2018).
- Kondolf, G. M., Rubin, Z. K. & Minear, J. T. Dams on the Mekong: cumulative sediment starvation. *Water Resour. Res.* **50**, 5158–5169 (2014).
- Schmitt, R. J. P. et al. Strategic basin and delta planning increases the resilience of the Mekong Delta under future uncertainty. *Proc. Natl Acad. Sci. USA* **118**, e2026127118 (2021).
- Schmitt, R. J. P. & Minderhoud, P. S. J. Data, knowledge, and modeling challenges for science-informed management of river deltas. *One Earth* **6**, 216–235 (2023).
- Kondolf, G. M. et al. Changing sediment budget of the Mekong: cumulative threats and management strategies for a large river basin. *Sci. Total Environ.* **625**, 114–134 (2018).
- Syvitski, J. et al. Earth's sediment cycle during the Anthropocene. *Nat. Rev. Earth Environ.* **3**, 179–196 (2022).
- Opperman, J. Tradeoffs between climate mitigation and adaptation: dams, sand, and substitutes. *Forbes* <https://www.forbes.com/sites/jeffopperman/2024/03/04/tradeoffs-between-climate-mitigation-and-adaptation-dams-sand-and-substitutes/> (2024).
- Li, D. et al. High Mountain Asia hydropower systems threatened by climate-driven landscape instability. *Nat. Geosci.* <https://doi.org/10.1038/s41561-022-00953-y> (2022).
- Zhang, T. et al. Warming-driven erosion and sediment transport in cold regions. *Nat. Rev. Earth Environ.* <https://doi.org/10.1038/s43017-022-00362-0> (2022).
- Wild, T. B. & Loucks, D. P. Managing flow, sediment, and hydropower regimes in the Sre Pok, Se San, and Se Kong Rivers of the Mekong basin. *Water Resour. Res.* **50**, 5141–5157 (2014).
- Schmitt, R. J. P., Bizzi, S., Castelletti, A., Opperman, J. J. & Kondolf, G. M. Planning dam portfolios for low sediment trapping shows limits for sustainable hydropower in the Mekong. *Sci. Adv.* **5**, eaaw2175 (2019).
- Hackney, C. R. et al. River bank instability from unsustainable sand mining in the lower Mekong River. *Nat. Sustain.* **3**, 217–225 (2020).
- Darby, S. E. et al. Fluvial sediment supply to a mega-delta reduced by shifting tropical-cyclone activity. *Nature* **539**, 276–279 (2016).
- Xu, B. & He, X. A physics-informed Bayesian storyline approach to assess sediment transport in the Mekong. *Water Resources Research* **58**, e2022WR032681 (2022).
- Syvitski, J. P. M. et al. Sinking deltas due to human activities. *Nat. Geosci.* **2**, 681–686 (2009).
- Bravard, J.-P., Goichot, M. & Tronchère, H. An assessment of sediment-transport processes in the Lower Mekong River based on deposit grain sizes, the CM technique and flow-energy data. *Geomorphology* **207**, 174–189 (2014).
- Intralawan, A., Wood, D., Frankel, R., Costanza, R. & Kubiszewski, I. Tradeoff analysis between electricity generation and ecosystem services in the Lower Mekong Basin. *Ecosyst. Serv.* **30**, 27–35 (2018).
- He, X. et al. Solar and wind energy enhances drought resilience and groundwater sustainability. *Nat. Commun.* **10**, 4893 (2019).
- Carlino, A., Schmitt, R., Clark, A. & Castelletti, A. Rethinking energy planning to mitigate the impacts of African hydropower. *Nat. Sustain.* <https://doi.org/10.1038/s41893-024-01367-x> (2024).
- Flecker, A. S. et al. Reducing adverse impacts of Amazon hydropower expansion. *Science* **375**, 753–760 (2022).
- Couto, T. B. A., Messenger, M. L. & Olden, J. D. Safeguarding migratory fish via strategic planning of future small hydropower in Brazil. *Nat. Sustain.* **4**, 409–416 (2021).
- Carlino, A. et al. Declining cost of renewables and climate change curb the need for African hydropower expansion. *Science* **381**, eadf5848 (2023).
- Chowdhury, A. F. M. K. et al. Enabling a low-carbon electricity system for Southern Africa. *Joule* <https://doi.org/10.1016/j.joule.2022.06.030> (2022).
- Mulugetta, Y. et al. Africa needs context-relevant evidence to shape its clean energy future. *Nat. Energy* <https://doi.org/10.1038/s41560-022-01152-0> (2022).
- Siala, K., Chowdhury, A. K., Dang, T. D. & Galelli, S. Solar energy and regional coordination as a feasible alternative to large hydropower in Southeast Asia. *Nat. Commun.* **12**, 4159 (2021).
- Wu, G. C. et al. Avoiding ecosystem and social impacts of hydropower, wind, and solar in Southern Africa's low-carbon electricity system. *Nat. Commun.* **15**, 1083 (2024).



40. Schmitt, R. J. P., Kittner, N., Kondolf, G. M. & Kammen, D. M. Joint strategic energy and river basin planning to reduce dam impacts on rivers in Myanmar. *Environ. Res. Lett.* **16**, 054054 (2021).
41. Opperman, J. J. et al. Balancing renewable energy and river resources by moving from individual assessments of hydropower projects to energy system planning. *Front. Environ. Sci.* **10**, 1036653 (2023).
42. Country Assessments, September 2021. *Climate Action Tracker* <http://climateactiontracker.org> (2021).
43. Schmitt, R. J. P., Bizzi, S., Castelletti, A. F. & Kondolf, G. M. Stochastic modeling of sediment connectivity for reconstructing sand fluxes and origins in the unmonitored Se Kong, Se San, and Sre Pok tributaries of the Mekong River: stochastic connectivity modelling. *J. Geophys. Res. Earth Surf.* **123**, 2–25 (2018).
44. Wild, T. B., Loucks, D. P., Annandale, G. W. & Kaini, P. Maintaining sediment flows through hydropower dams in the Mekong River Basin. *J. Water Resour. Plan. Manag.* **142**, 05015004 (2016).
45. Dunn, F. E. & Minderhoud, P. S. J. Sedimentation strategies provide effective but limited mitigation of relative sea-level rise in the Mekong delta. *Commun. Earth Environ.* **3**, 2 (2022).
46. Edmonds, D. A. et al. Land loss due to human-altered sediment budget in the Mississippi River Delta. *Nat. Sustain.* <https://doi.org/10.1038/s41893-023-01081-0> (2023).
47. Chapman, A. D. & Darby, S. E. Dams and the economic value of sediment in the Vietnamese Mekong Delta. *Ecosyst. Serv.* **32**, 110–111 (2018).
48. Schmitt, R. J. P., Bizzi, S., Castelletti, A. & Kondolf, G. M. Improved trade-offs of hydropower and sand connectivity by strategic dam planning in the Mekong. *Nat. Sustain.* **1**, 96–104 (2018).
49. Almeida, R. M. et al. Strategic planning of hydropower development: balancing benefits and socioenvironmental costs. *Curr. Opin. Environ. Sustain.* **56**, 101175 (2022).
50. Dammed in the Mekong: averting an environmental catastrophe. *International Crisis Group* <https://www.crisisgroup.org/asia/south-east-asia/cambodia-thailand-china/343-dammed-mekong-averting-environmental-catastrophe> (2024).
51. Barbarossa, V. & Schmitt, R. J. P. Strategic restoration-development mitigates tradeoffs between hydropower and fish habitat fragmentation in the Mekong. *One Earth* **7**, 1096–1107 (2024).
52. Chowdhury, A. F. M. K., Dang, T. D., Bagchi, A. & Galelli, S. Expected benefits of Laos' hydropower development curbed by hydroclimatic variability and limited transmission capacity: opportunities to reform. *J. Water Resour. Plan. Manag.* **146**, 05020019 (2020).
53. Zhang, B. et al. Dual water-electricity cooperation improves economic benefits and water equality in the Lancang-Mekong River Basin. *Nat. Commun.* **14**, 6228 (2023).
54. Lehner, B. et al. High-resolution mapping of the world's reservoirs and dams for sustainable river-flow management. *Front. Ecol. Environ.* **9**, 494–502 (2011).
55. Almeida, R. M. et al. Reducing greenhouse gas emissions of Amazon hydropower with strategic dam planning. *Nat. Commun.* **10**, 4281 (2019).
56. Galelli, S., Dang, T. D., Ng, J. Y., Chowdhury, A. F. M. K. & Arias, M. E. Opportunities to curb hydrological alterations via dam re-operation in the Mekong. *Nat. Sustain.* <https://doi.org/10.1038/s41893-022-00971-z> (2022).
57. Neitsch, S. L., Arnold, J. G., Kiniry, J. R. & Williams, J. R. *Soil and Water Assessment Tool: Theoretical Documentation Version 2009*. Report No. 406 (Texas Water Resources Institute, 2011).
58. Haimes, Y., Lasdon, L. & Wismer, D. On a bicriterion formulation of the problems of integrated system identification and system optimization. *IEEE Trans. Syst. Man Cybern.* **SMC-1**, 296–297 (1971).
59. Schmitt, R. J. P., Bizzi, S. & Castelletti, A. Tracking multiple sediment cascades at the river network scale identifies controls and emerging patterns of sediment connectivity. *Water Resour. Res.* **52**, 3941–3965 (2016).
60. Wan, W., Zhao, J., Papat, E., Herbert, C. & Döll, P. Analyzing the impact of streamflow drought on hydroelectricity production: a global-scale study. *Water Res.* **57**, e2020WRO28087 (2021).
61. Kondolf, G. M. et al. Sustainable sediment management in reservoirs and regulated rivers: experiences from five continents. *Earth's Future* **2**, 256–280 (2014).
62. Brune, G. M. Trap efficiency of reservoirs. *Eos (Washington DC)* **34**, 407–418 (1953).
63. Cococcioni, M. & Fiaschi, L. The Big-M method with the numerical infinite M. *Optim. Lett.* **15**, 2455–2468 (2021).
64. Li, Y. & Chang, Y. Infrastructure investments for power trade and transmission in ASEAN + 2: costs, benefits, long-term contracts and prioritized developments. *Energy Econ.* **51**, 484–492 (2015).
65. Watcharejyothin, M. & Shrestha, R. M. Effects of cross-border power trade between Laos and Thailand: energy security and environmental implications. *Energy Policy* **37**, 1782–1792 (2009).
66. Demski, C. National context is a key determinant of energy security concerns across Europe. *Nat. Energy* **3**, 882–888 (2018).
67. Shen, J., Cheng, C., Shen, Q., Lu, J. & Zhang, J. Overview of China's hydropower absorption: evolution, problems, and suggested solutions. *IET Renew. Power Gener.* **13**, 2491–2501 (2019).

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## Author contributions

X.H. conceived the research. B.X. and Z.L. performed the research. B.X. and X.H. analysed the results and drafted the manuscript. S.Y. provided comments and revised the manuscript. R.J.P.S. contributed to experimental design, research framing and writing of the manuscript.

## Competing interests

The authors declare no competing interests.

## Additional information

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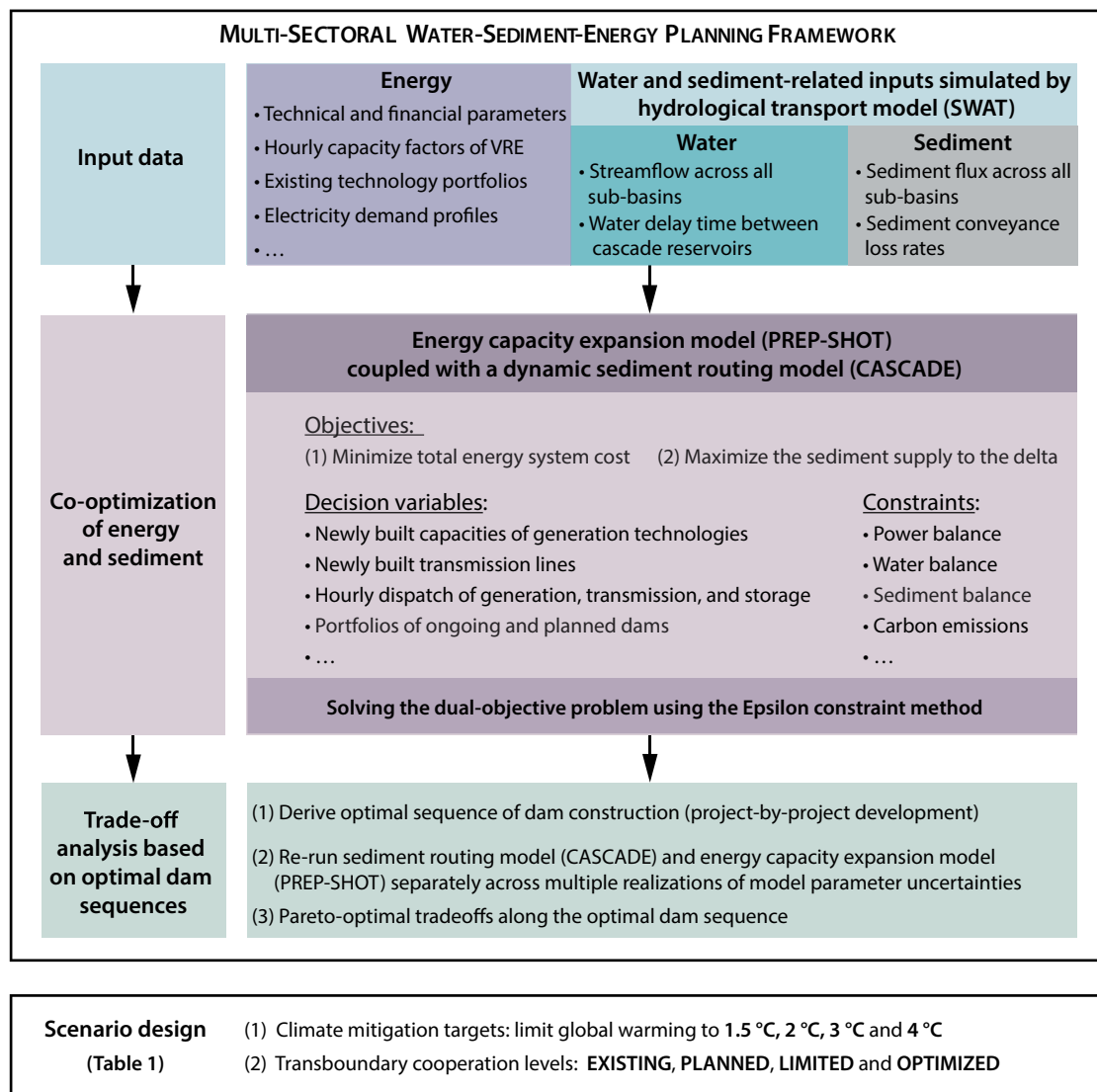
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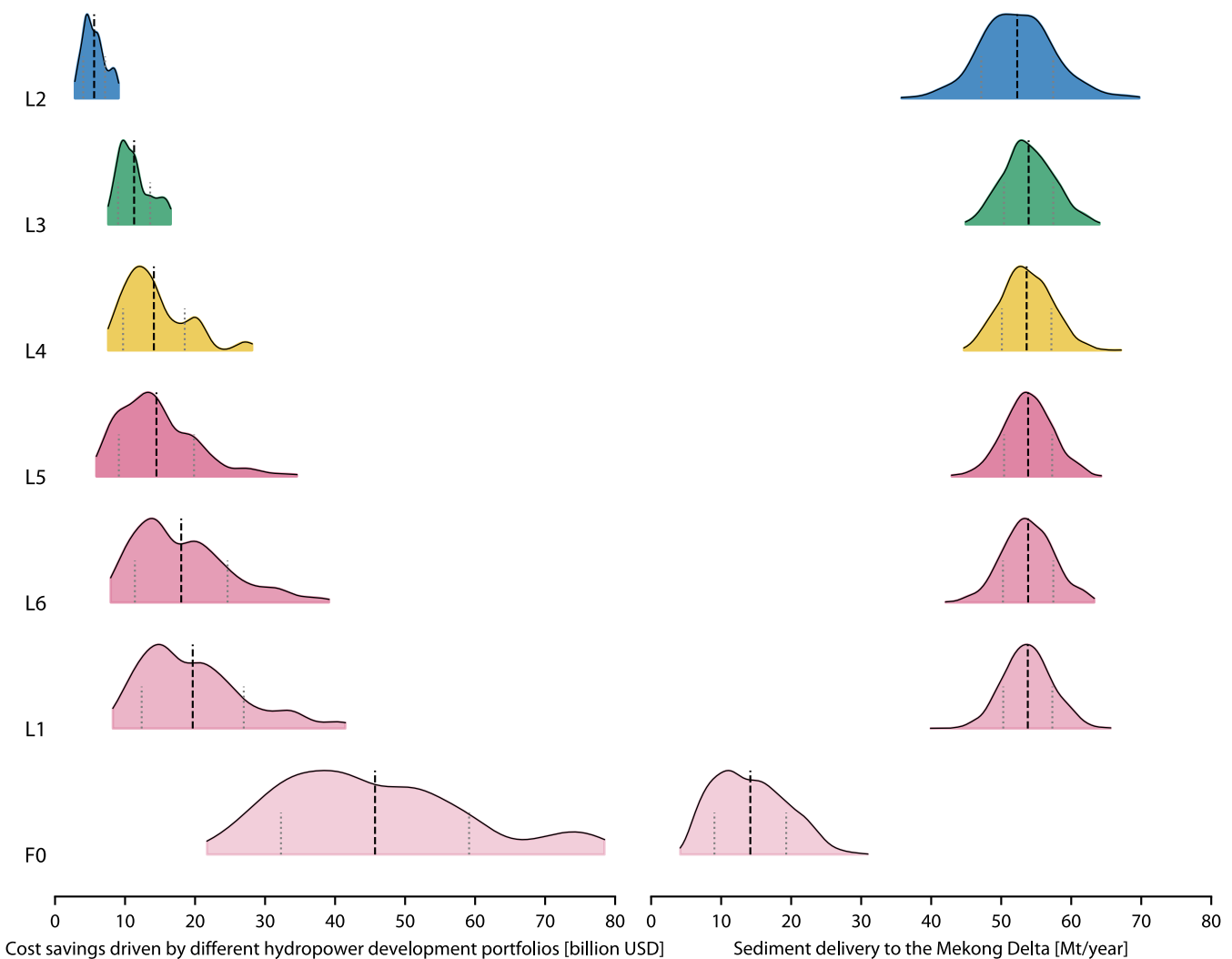
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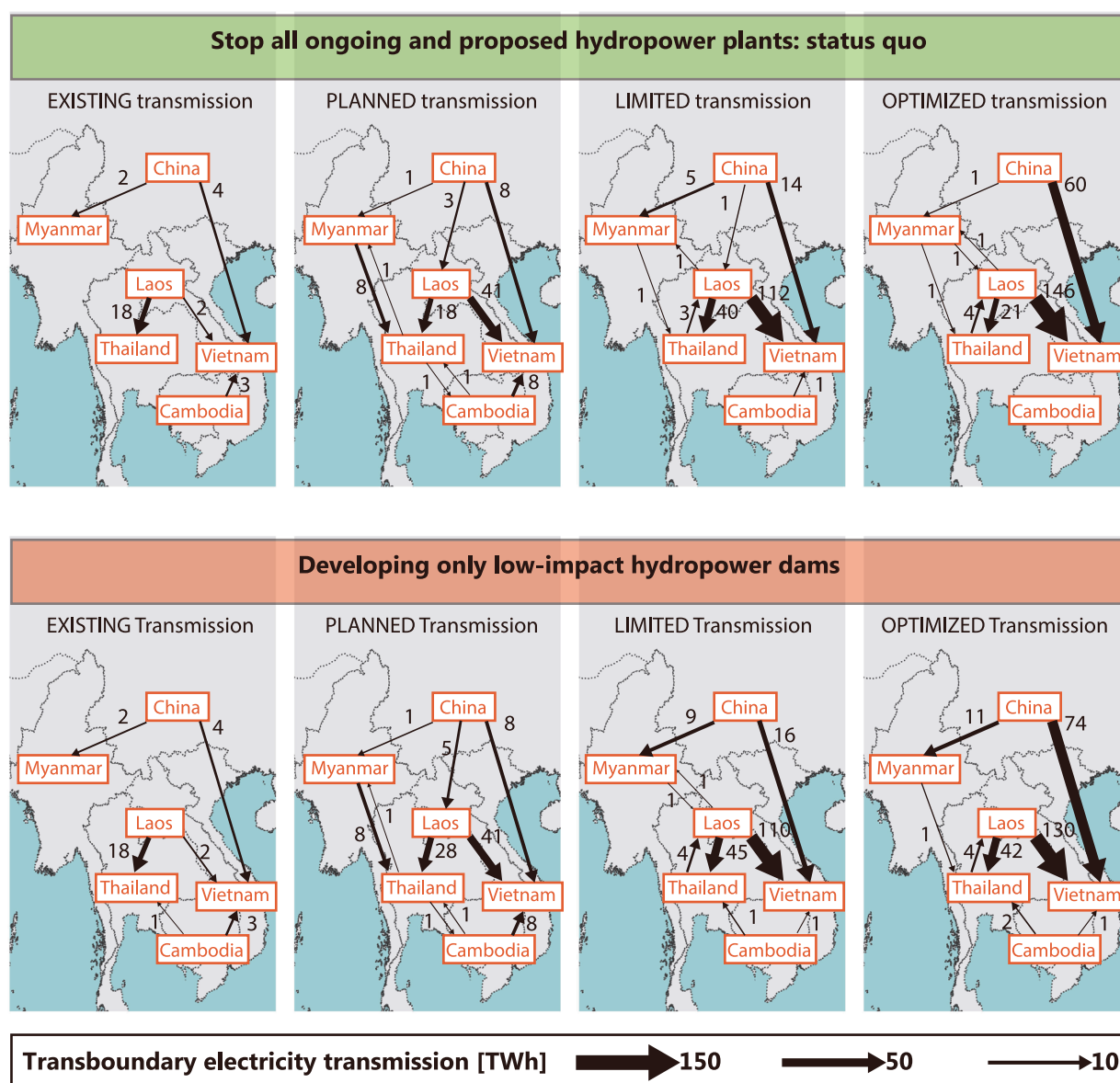
**Extended Data Fig. 1 | Overview of the integrated water-sediment-energy modeling framework.** VRE: variable renewable energy; SWAT: Soil and Water Assessment Tool; PREP-SHOT: Pathways for Renewable Energy Planning coupling Short-term Hydropower OperaTion; CASCADE: Catchment Sediment Connectivity And Delivery.



**Extended Data Fig. 2 | System cost savings and sediment outcomes under different hydropower scenarios.** The left panel shows cost savings (billion USD), calculated as total system cost differences under seven scenarios (F0 and L1–L6) relative to a scenario without new hydropower plants (S0). The right panel shows sediment delivery to the Mekong Delta (Mt per year). Both panels use Kernel Density Estimates (KDEs) to visualize the uncertainty distributions for each scenario. Distributions are based on 729 parameter combinations for cost calculations and 1,000 combinations for sediment calculations. For each scenario, the solid black line shows the distribution shape, while the dashed vertical line indicates the mean value across samples. The dotted

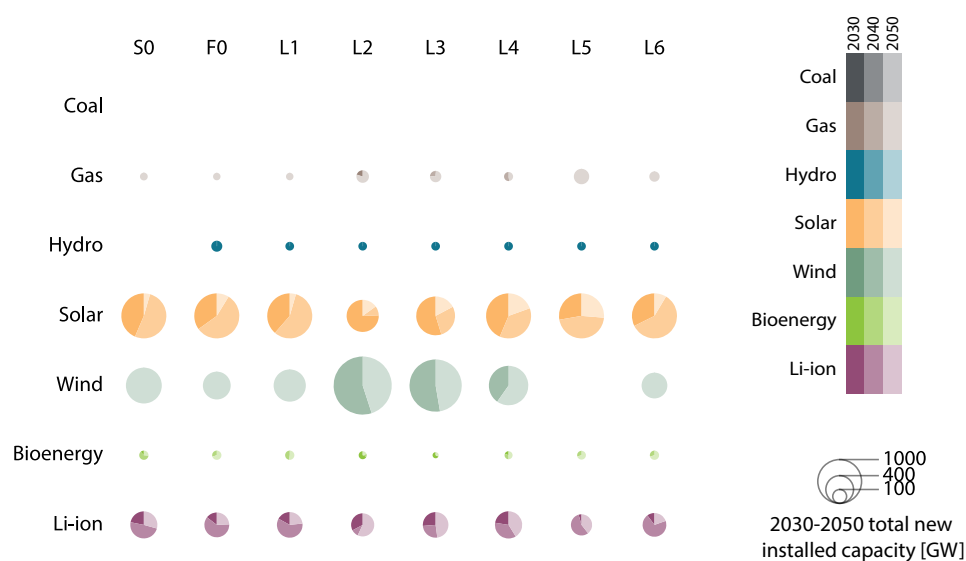
vertical lines represent  $\pm 1$  standard deviation around the mean, reflecting the spread of the uncertainty distribution. Further details on the uncertainty analysis and parameter combinations are provided in Supplementary Note 1. Scenario S0 represents the status quo hydropower portfolio under the T1.5 °C decarbonization target and OPTIMIZED transboundary transmission capacity. Scenario F0 assumes the same climate and transmission targets as S0, but with full hydropower development. Scenarios L1–L6 explore development of only low-impact dams: L1 aligns with S0's climate and transmission settings, L2–L4 reflect varying transmission restrictions based on L1, and L5–L6 represent different decarbonization targets based on L1.



**Extended Data Fig. 3 | Transboundary electricity transmission in 2030.**

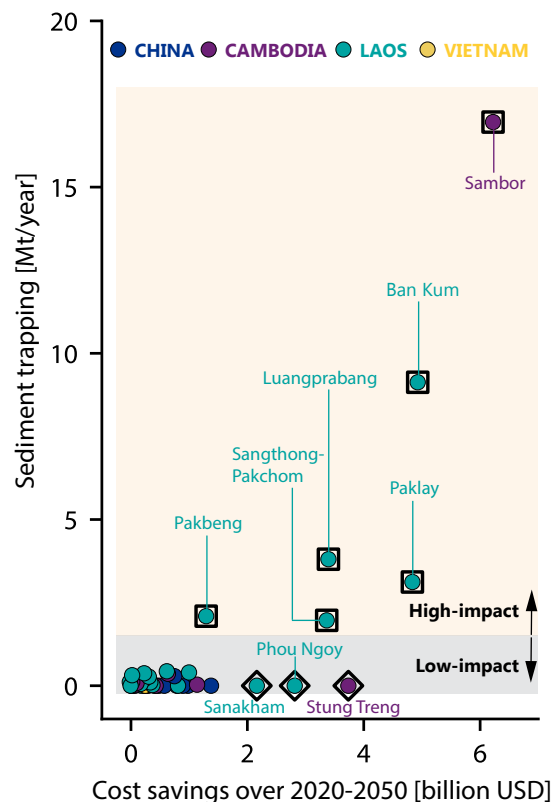
Results presented here are based on scenarios with 1.5 °C compatible climate mitigation target. Four transmission scenarios, namely EXISTING, PLANNED, LIMITED, and OPTIMIZED transmission, are depicted from left to right. The top row features the scenarios where all the ongoing and planned hydropower plants are stopped from 2022 onwards, while the bottom row shows the scenarios

where only the low-impact hydropower dams are developed. Thailand and Vietnam emerge as the primary electricity importers, driven by future electricity demand projections. Additionally, four other countries serve as major electricity exporters, with the Laos being the largest exporter. As the cross-country cooperation in electricity trade intensifies, the volume of electricity trade also escalates, particularly for China-Vietnam and Laos-Vietnam transmission lines.



**Extended Data Fig. 4 | Composition of newly installed capacity for the eight highlighted scenarios from 2030 to 2050.** Pie chart size corresponds to the magnitude of the new capacity. Colors represent different generation

technologies. Opacity levels within the charts indicate the progression of years (lighter shades denote later years), allowing visualization of changes in the electricity generation mix over time.



**Extended Data Fig. 5 | Incremental impacts of individual dams on total energy system cost savings and sediment trapping.** Results shown here are based on the scenario with optimized transboundary transmission and T1.5 °C climate mitigation target. The changes observed at adjacent points in the main text Fig. 2a correspond to the incremental impacts of adding each hydropower plant along the optimal development sequence. Among the 53 planned and ongoing dams, 44 trap less than 0.5 Mt sediment per year and provide minimal cost

savings to the energy system (< 2 billion USD over 2020-2050). Six dams bring high benefits for the energy system but also have high impacts on the sediment supply (that are, Sambor, Ban Kum, Paklay, Luangprabang, Sangthong-Pakchom, and Pakbeng). Additionally, three dams offer high benefits (> 2 billion USD over 2020-2050) with low impacts on sediment supply (namely, Stung Treng, Phou Ngoy, and Sanakham).

**Extended Data Table 1 | Key PREP-SHOT inputs**

Parameter [Unit]	Description
Historical capacity [MW]	Installed capacity by technology and zone for each year, reflecting the cumulative years of operation since the start of the planning horizon.
Capacity factor [-]	Capacity factor of each non-dispatchable technology.
Carbon emission limit [tonne CO <sub>2</sub> ]	Annual carbon emission limit for each zone.
Emission factor [tonne CO <sub>2</sub> /MWh]	CO <sub>2</sub> emissions per unit of electricity generation by technology.
Water delay time [-]	Time lag between upstream release and downstream arrival along reservoir links, expressed in model time steps.
Demand [MW]	Electricity demand by balancing authority.
Discount factor [-]	Annual discount factor for economic evaluation.
Distance [km]	Distance between zone pairs for transmission planning.
Discharge efficiency [-]	Electricity discharge efficiency for storage technologies.
Charge efficiency [-]	Electricity charging efficiency for storage technologies.
Energy to power ratio [MWh/MW]	Energy to power ratio for storage technologies, defined as a storage technology's energy capacity divided by its power capacity.
Fuel price [USD/MWh]	Fuel price by technology and year.
Inflow [m <sup>3</sup> /s]	Lateral inflow of each reservoir.
Initial energy storage level [-]	Initial state of charge for storage technologies, expressed as a fraction of maximum storage capacity.
Lifetime [year]	Technical lifetime of each technology.
New technology lower bound [MW]	Minimum allowable new capacity additions for each technology and investment year.
New technology upper bound [MW]	Maximum allowable new capacity additions for each technology and investment year.
Ramp down limit [%/hour]	Maximum allowable decrease in power output per hour, expressed as a percentage of installed capacity.
Ramp up limit [%/hour]	Maximum allowable increase in power output per hour, expressed as a percentage of installed capacity.
Reservoir characteristics	Reservoir characteristics data includes designed water head [m], maximum storage [m <sup>3</sup> ], minimum storage [m <sup>3</sup> ], operational efficiency [-], area of affiliation [-], installed capacity [MW], maximum power output [MW], minimum power output [MW], maximum outflow [m <sup>3</sup> /s], minimum outflow [m <sup>3</sup> /s], and maximum generation outflow [m <sup>3</sup> /s].
Reservoir storage upper bound [m <sup>3</sup> ]	Allowable maximum storage volume of the reservoir.
Reservoir storage lower bound [m <sup>3</sup> ]	Allowable minimum storage volume of the reservoir.
Final reservoir storage level [m <sup>3</sup> ]	Reservoir storage volume at the end of the operational period.
Initial reservoir storage level [m <sup>3</sup> ]	Reservoir storage volume at the start of the operational period.
Technology fixed OM cost [USD /MW/year]	Annual fixed operation and maintenance cost per unit of installed capacity.
Technology variable OM cost [USD/MWh/year]	Annual variable operation and maintenance cost per unit of electricity generated.
Technology investment cost [USD/MW]	Investment cost per unit of installed capacity.
Technology portfolio [MW]	Existing installed capacity across all zones.
Technology upper bound [MW]	Maximum installed capacity by technology.
Transmission line existing capacity [MW]	Installed transmission capacity between zones (blank if no line exists).
Transmission line efficiency [-]	Fractional power transfer efficiency of transmission lines.
Transmission line fixed OM cost [USD/MW/year]	Annual fixed operation and maintenance cost per unit of installed transmission capacity.
Transmission line variable OM cost [USD/MWh/year]	Variable operation and maintenance cost per unit of electricity transmitted.
Transmission line investment cost [USD/MW/km]	Investment cost per unit of transmission capacity and line length.
Transmission line lifetime [year]	Technical lifetime of transmission assets.
Technology type	Category or classification of each technology (e.g., dispatchable, non-dispatchable, storage).
Reservoir tailrace level-discharge function	Relationship between tailrace water level and total outflow for each reservoir.
Reservoir forebay level-volume function	Relationship between forebay water level and storage volume for each reservoir.



**Extended Data Table 2 | Key PREP-SHOT outputs**

Variable [Unit]	Description
Electricity exports [MWh]	Electricity transmitted from Zone 1 to Zone 2 before accounting for transmission losses.
Electricity imports [MWh]	Electricity received in Zone 2 from Zone 1 after accounting for transmission losses.
Electricity generation [MW]	Power output from each generation technology in each time period.
Installed capacity [MW]	Maximum rated capacity of each generation technology, reported by zone, year, and technology.
Carbon emissions [tonne CO <sub>2</sub> ]	Carbon dioxide emissions from electricity generation across the planning horizon.
Storage charging [MW]	Electricity charging rate for each storage technology during each time period.
Total system costs [USD]	Sum of investment, fixed O&M, and variable O&M costs for the entire system over the planning horizon.
System cost breakdown [USD]	Same costs as above, reported by zone, year, and technology.
Variable O&M costs [USD]	Total variable operation and maintenance cost over the planning horizon, including generation, transmission, and fuel costs.
Variable O&M cost breakdown [USD]	Same variable O&M costs, reported by zone, year, and technology.
Fixed O&M costs [USD]	Total fixed operation and maintenance cost over the planning horizon, including costs for both generation technologies and transmission lines.
Fixed O&M cost breakdown [USD]	Same fixed O&M costs, reported by zone, year, and technology.
Generation investments [USD]	Total investment cost for electricity generation technologies over the planning horizon.
Generation investment breakdown [USD]	Same technology investment costs, reported by zone, year, and technology.
Transmission investments [USD]	Total investment cost of transmission lines over the planning horizon.
Transmission investment breakdown [USD]	Same transmission investment costs, reported by zone, year, and technology.
Reservoir turbine outflow [m <sup>3</sup> /s]	Water released from reservoirs through turbines for electricity generation in each time period.
Reservoir spills [m <sup>3</sup> /s]	Water released from reservoirs through spillways, not used for electricity generation.

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For a reference copy of the document with all sections, see [nature.com/documents/nr-reporting-summary-flat.pdf](https://nature.com/documents/nr-reporting-summary-flat.pdf)

## Ecological, evolutionary & environmental sciences study design

All studies must disclose on these points even when the disclosure is negative.

Study description	This study develops a fully coupled reservoir operation and energy expansion model to quantify the economic and sediment benefits attained from different hydropower investment strategy in a high-variable renewable energy (VRE) future.
Research sample	Our study considers 53 planned and ongoing hydropower stations in Mekong River Basin.
Sampling strategy	NA
Data collection	Key data/parameters are collected from existing literature and open source data platforms. Decarbonization target data are available via the Climate Action Tracker (CAT) <a href="https://climateactiontracker.org/">https://climateactiontracker.org/</a> . Solar and wind capacity factor data are accessible through <a href="https://www.renewables.ninja">https://www.renewables.ninja</a> . Dam and reservoir characteristics are available in the supplementary material of Refs ( <a href="https://www.science.org/doi/10.1126/sciadv.aaw2175">https://www.science.org/doi/10.1126/sciadv.aaw2175</a> and <a href="https://doi.org/10.1029/2020WR028087">https://doi.org/10.1029/2020WR028087</a> ). Public datasets used to drive SWAT model simulations are available via SRTM 90m Digital Elevation Database v4.1 – CGIAR-CSI ( <a href="https://cgiarcsi.community">cgiarcsi.community</a> ) (DEM), ISLSCP II IGBP DISCover and SiB Land Cover, 1992-1993, <a href="https://doi.org/10.3334/ORNLDAAAC/930">https://doi.org/10.3334/ORNLDAAAC/930</a> (Land-use map), and Harmonized world soil database v1.2   FAO SOILS PORTAL   Food and Agriculture Organization of the United Nations (Soil map). Measurements of streamflow and suspended sediment concentration in the Mekong River Basin are obtained from the Mekong River Commission (MRC): <a href="https://portal.mrcmekong.org/home">https://portal.mrcmekong.org/home</a> . All other data used in the optimization are provided in the Supplementary Information and are cited from publicly available sources.
Timing and spatial scale	The time and spatial scale of data used in the SWAT Model: DEM, 90m×90m, static data in 2000; Land-use map, 0.25 degree × 0.25 degree, static data in 1992; Soil map, 0.5 degree × 0.5 degree, static data in 2008; Precipitation, 0.5 degree × 0.5 degree, Daily in 1960–2005; Temperature (maximum and minimum), 0.5 degree × 0.5 degree, Daily in 1960–2005; Solar radiation/Relative humidity/Wind speed, 0.5 degree × 0.5 degree, Daily in 1960–2005; Streamflow, 6 Stations, Daily in 1962–2005; Suspend sediment concentration, 6 Stations, Daily in 1962–1990.

Data exclusions	No data were excluded from the analyses.
Reproducibility	Results can be reproduced using the SWAT, PREP-SHOT, CASCADE, and the datasets mentioned in paper.
Randomization	NA
Blinding	NA

Did the study involve field work? ☐ Yes ☒ No

## Reporting for specific materials, systems and methods

We require information from authors about some types of materials, experimental systems and methods used in many studies. Here, indicate whether each material, system or method listed is relevant to your study. If you are not sure if a list item applies to your research, read the appropriate section before selecting a response.

### Materials & experimental systems

n/a	Involved in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> Antibodies
<input checked="" type="checkbox"/>	<input type="checkbox"/> Eukaryotic cell lines
<input checked="" type="checkbox"/>	<input type="checkbox"/> Palaeontology and archaeology
<input checked="" type="checkbox"/>	<input type="checkbox"/> Animals and other organisms
<input checked="" type="checkbox"/>	<input type="checkbox"/> Clinical data
<input checked="" type="checkbox"/>	<input type="checkbox"/> Dual use research of concern

### Methods

n/a	Involved in the study
<input checked="" type="checkbox"/>	<input type="checkbox"/> ChIP-seq
<input checked="" type="checkbox"/>	<input type="checkbox"/> Flow cytometry
<input checked="" type="checkbox"/>	<input type="checkbox"/> MRI-based neuroimaging