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Current Opinion in Environmental Sustainability

Strategic planning of hydropower development: balancing benefits and socioenvironmental costs

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Hydropower continues to expand globally as the power sector transitions away from carbon-intensive fossil fuels. New dam sites vary widely in the magnitude of their adverse effects on natural ecosystems and human livelihoods. Here, we discuss how strategic planning of hydropower expansion can assist decision makers in comparing the benefits of building dams against their socioenvironmental impacts. Advances in data availability and computational analysis now enable accounting for an increasing array of social and environmental metrics at ever-larger spatial scales. In turn, expanding the spatial scale of planning yields more options in the quest to improve both economic and socioenvironmental outcomes. There remains a pressing need to incorporate climate change into hydropower planning. Ultimately, these innovations in evaluating prospective dam sites should be integrated into strategic planning of the entire energy system to ensure that social and environmental disruption of river systems is minimized.

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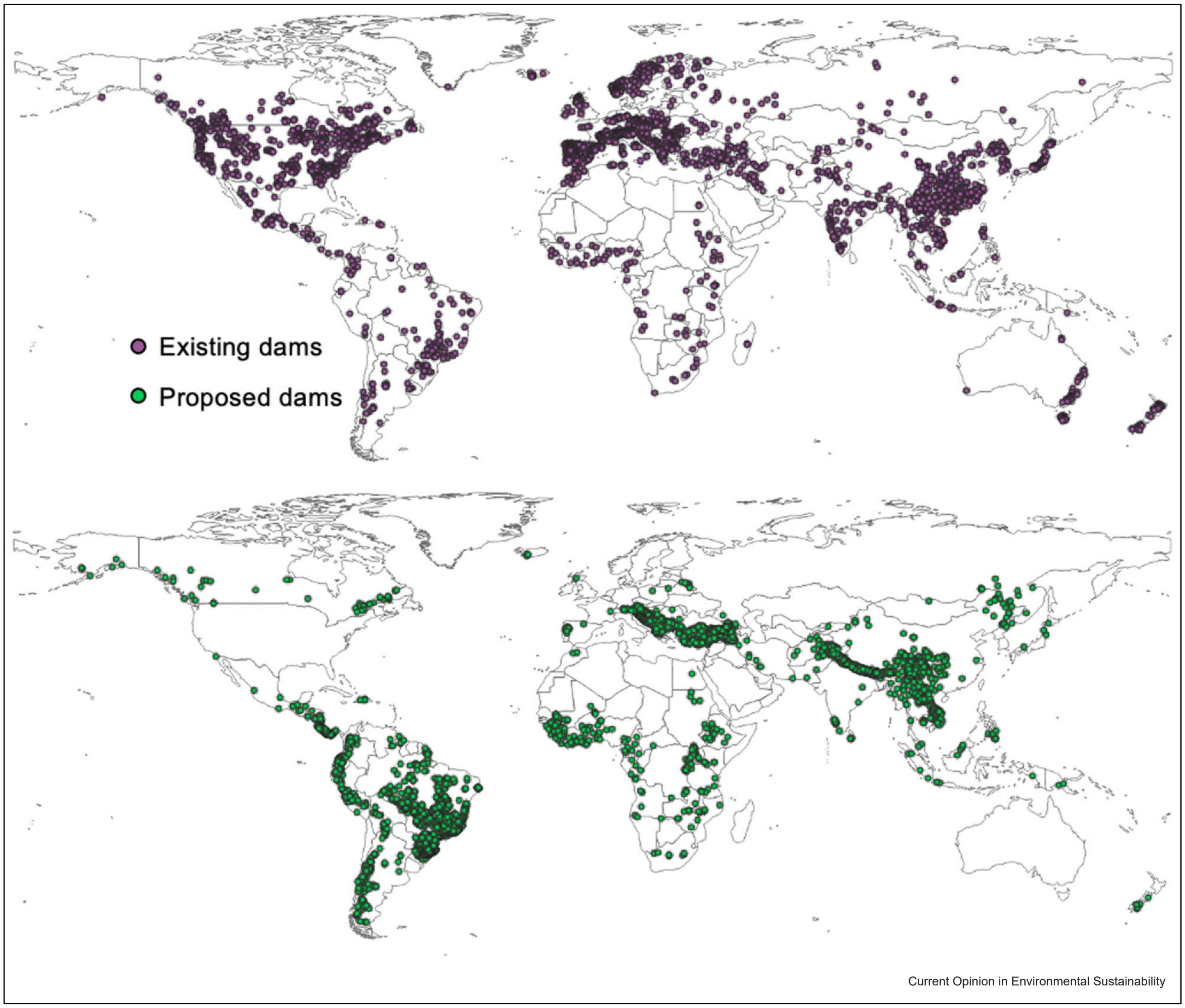
Introduction

By 2030, about 80% of new global electricity demand will be satisfied by renewable sources [1]. The largest source of renewable electricity is hydropower, and dam construction is expected to continue in the coming decades [2]. While most existing dams are in developed countries [3], the majority of future hydropower projects will be built in the Global South (Figure 1), where most of the world's major free-flowing rivers remain [4]. Tapping the enormous hydropower potential of river basins like the Amazon, Congo, Irrawaddy, and Mekong could jeopardize their biological diversity as well as the livelihoods of millions of people [5]. Recent analyses of the social and ecological impacts of hydropower development in major basins worldwide indicate sobering repercussions for biodiversity [6–8], food security [9,10], greenhouse gas emissions [11–13], local climate [14,15], sediment and nutrient transport [16,17], habitat connectivity [18,19], natural flow regimes [4,20,21], and human settlements [22,23].

Dam siting decisions are commonly driven by political and engineering factors on a single-project basis [24]. Among the rare instances of planning for a portfolio of multiple dams within a river basin, some efforts have

Figure 1

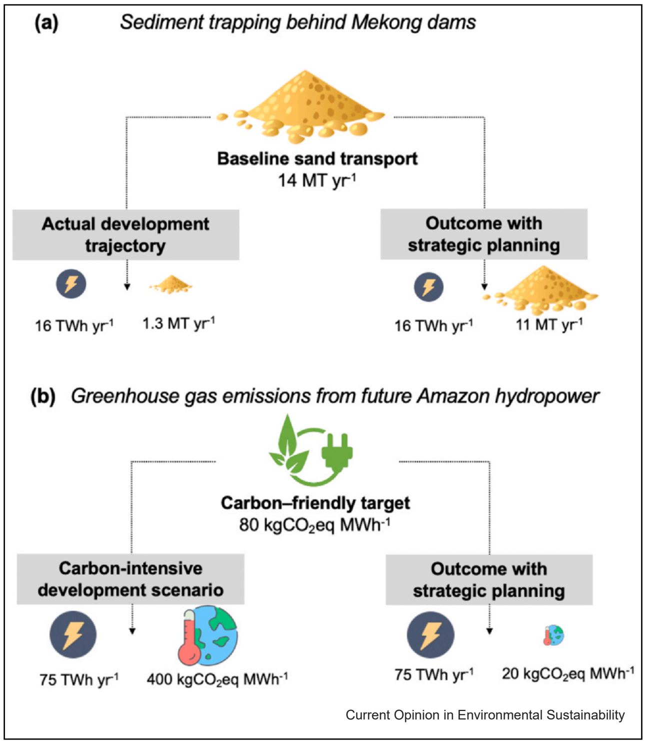


Maps of existing (> 0.1 km^3) and proposed (> 1 MW) hydropower dams.
Source: Global Dam Watch (http://globaldamwatch.org).

simply balanced money-losing dams for irrigation supplies with economically attractive hydropower projects [25]. Real-world dam planning typically lacks basin-wide assessments of cumulative benefits and socio-environmental impacts; instead, individual dams are considered based only on a limited range of local-scale benefits and costs [21]. Such single-project evaluations ignore the fact that multiple dams within the same river network typically have cumulative impacts on the environment.

In contrast to single-project assessments, strategic planning aims to inform decisions by comparing a wide range of alternatives from the outset [26]. Strategic hydropower planning enables decision makers to assess the impacts and benefits of dam portfolios throughout the basin (or larger region), focusing on the collective good that could be achieved from an ideal subset of potential dam sites (Figure 2). While strategic spatial planning is well established in environmental management [27], new data, models and computational methods have only recently enabled its application at the scale of large river basins. Now, environmental organizations are promoting strategic dam planning (e.g., 'Hydropower by Design' [28]), and a growing body of literature [10,11,17,19,29,30] reveals avoidable collateral damage from the uncoordinated selection of dam sites (Figure 3). For example, in a major sub-basin of the Mekong, coordinated selection of dams could have tapped ~70% of the basin's hydropower potential while interrupting

Figure 2



Quantifying the benefits of basin-wide strategic planning**.** **(a)** For the ‘3S’ region of the Mekong River basin, a strategic planning approach could have produced the same generation as the actual development trajectory, but maintained eight times as much sand exported from the basin to the downstream delta [29]. **(b)** In the Amazon basin, future dam development could follow sharply contrasting paths in terms of carbon intensity, as illustrated by two scenarios to achieve ~20% of the basin’s proposed hydropower potential. A portfolio of strategically selected dams with high power densities (MW km^{-2}) can produce electricity emitting 20 times less carbon than portfolios of lowland dams with poor power densities [11]. For context, the average emission intensity of solar photovoltaics and natural gas is 48 kg CO$_2$eq MWh^{-1} and 490 kg CO$_2$eq MWh^{-1}, respectively [33]. The large variation in hydropower’s carbon intensity outcomes stems from highly variable ratios of electricity generation capacity per unit of flooded area (also known as ‘power density’), as well as greenhouse gas emission rates from the surface of reservoirs.
Adapted from J Opperman, et al. [34].

about 20% of the sand-sized sediment load. Unfortunately, the current project-by-project development trajectory has resulted in trapping about 90% of sediments while harnessing only 50% of the basin's hydropower potential [29]. In the Amazon, a strategic portfolio of new dams could meet future energy targets while emitting less greenhouse gases per unit energy than solar power, whereas project-by-project planning could result in dam portfolios emitting as much per unit energy as fossil fuel sources [11]. In coastal river basins in Africa, it has been shown that natural flow regimes can be maintained with relatively small sacrifices in energy generation [31,32].

Even though annual investment in hydropower has been declining with the upsurge in wind and solar photovoltaics [34], widely accepted scenarios of energy development to meet climate change targets still include significant increases in hydropower development by 2050—from 50% [35] to nearly 100% [36] relative to current capacity. Even a 50% increase in global hydropower capacity would likely require damming a majority of the remaining large free-flowing rivers in the tropics [21]. With looming conflicts between global climate action and the conservation of connected river systems, strategic planning of future hydropower portfolios is more urgent than ever.

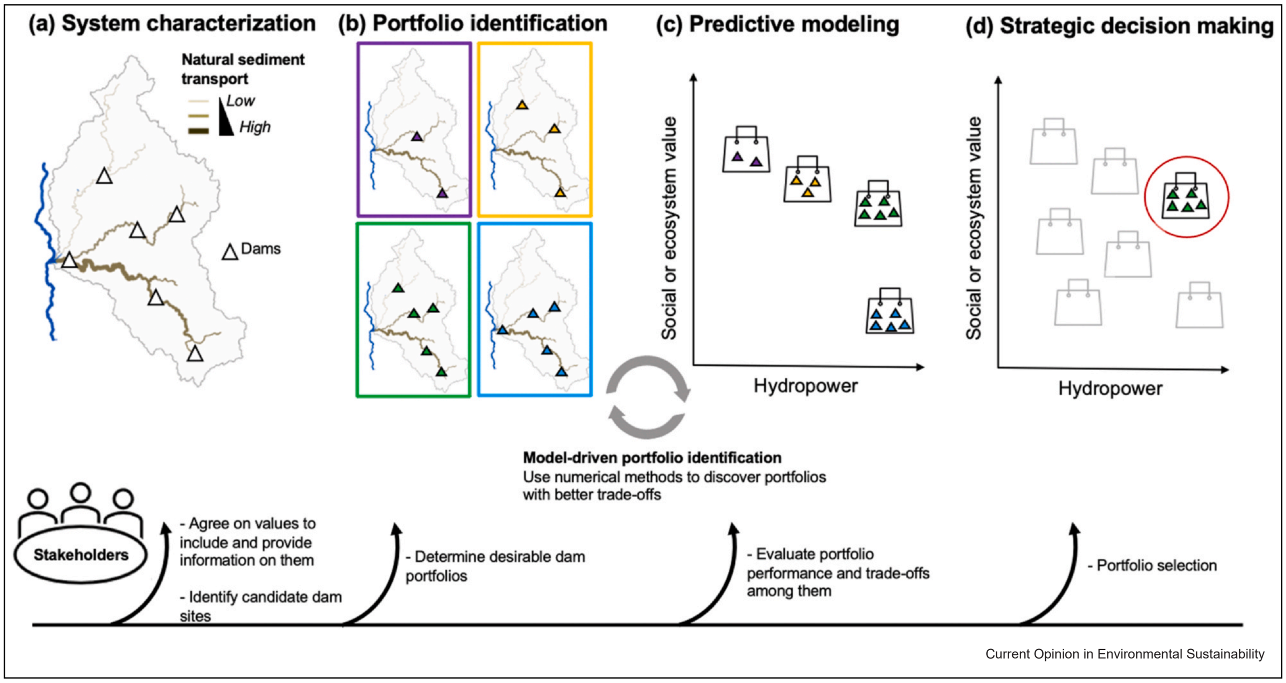
Here, we summarize emerging principles and discuss the remaining limitations of research on strategic hydropower planning. Further, we recommend pathways for minimizing socioenvironmental disruption of future hydropower development. Our hope is to provide a blueprint to support strategic decisions that balance benefits against the social and environmental costs of dams. While our focus is on strategic hydropower planning, we note that researchers [30,37] and environmental organizations [21,34] are increasingly exploring ways to integrate strategic planning from hydropower with energy system planning, which can lessen environmental impacts and reduce reliance on hydropower.

Different dams, different impacts, and benefits

Strategic planning of dam sites is intended to recommend suites of locations that could achieve desired service levels yet minimize collective adverse impacts. The efficiency gains of such formal analyses increase with spatial heterogeneity among potential dam sites in ecosystem and social values, and the number of candidate sites under consideration. Strategic planning becomes less useful when the collective power generation being sought approaches the total for all candidate sites, or in rare situations when the benefits and negative impacts of each dam are independent of the existence of other dams. Analysis typically begins only after a technical design and operation rules are tailored to each site, yielding a unique set of construction cost, adverse impacts, and benefits for each dam. Identifying an ideal portfolio of hydropower sites then involves trading off these impacts and benefits within the constraints of meeting an overall electricity production goal. Analytically, this represents a multiobjective optimization problem where many — and often competing — social, environmental, and economic objectives need to be balanced.

In broad terms, dams can be distinguished by their location in the river network (i.e. mainstem versus tributary dams) and their design (i.e. storage versus run-of-

Figure 3



Four core phases of strategic hydropower planning: **(a)** characterization of natural processes and human values (in this example, natural sediment transport); **(b)** identification of dam siting configurations (or 'portfolios'), **(c)** quantification of the performance of the identified portfolios (energy, economic, social, environmental), which can be refined using model-driven portfolio discovery and optimization; and **(d)** selection of dam portfolio with acceptable trade-offs between impacts and benefits. Stakeholder participation is key throughout the process.

river). In terms of location, mainstem dams generally generate more electricity but have higher environmental impacts, as they are more disruptive for the river network integrity as a whole [38]. In terms of design, storage and run-of-river project types play different roles from an energy and water systems perspective, and these differences need to be acknowledged in energy system planning. Storage hydropower includes a dammed reservoir that provides more reliable energy, but at the expense of higher environmental costs. Deliberately storing and releasing water allows for better balancing seasonal variation in water availability for energy generation and consumptive demands; for instance, peak electricity demand for cooling buildings sometimes coincides with low water inputs from precipitation. In addition, storage projects can allow for multiple uses of the reservoir (e.g. irrigation, water supply, flood control, recreation), or can be designed for pumped storage of energy to overcome demand–supply mismatches in power grids [39]. In contrast, run-of-river projects lack those ancillary capacities, and their hydropower generation is limited by the instantaneous water availability, making them more susceptible to climatic variability and less suitable to balance renewable energy grids [40]. Although commonly viewed as more environmentally friendly than storage designs, run-of-river projects can also be highly disruptive, with negative consequences for downstream hydrology, water quality, sediment and river network connectivity, fisheries, and biodiversity [41–43].

Innovations in strategic planning of hydropower development

Conceptual studies have postulated several design principles for lowering the impact of hydropower [38]. In the past few years, a growing number of quantitative analyses have addressed these principles, yet the default for hydropower development in most of the world remains a project-by-project approval approach with no portfolio considerations. As hydropower development is promoted to meet future climate goals, and in the face of ongoing losses of river ecosystem services globally, it is imperative that research innovations are transferred into real-world decision support tools for strategic planning.

Over the past few years, most large-scale academic studies on strategic spatial planning have optimized hydropower generation for individual environmental criteria, such as fish diversity [10], greenhouse gas emissions [11], sediment transport [17,29], and river network connectivity [19]. Because any particular dam might perform well for some criteria and poorly for others, dam portfolios that perform well across all environmental objectives might not always exist [44].

Whole-basin optimization of hydropower production for a suite of social and environmental objectives is still rare, although there are a few early applications [32,44–46]. Data availability plays a large role in this limitation, as strategic planning requires modeling outcomes for different dam portfolios on a river network scale (Figure 2). Data to parametrize models are scarce, and include technical information (e.g. hydropower project characteristics, water and energy demands, operating rules) and characterization of natural and social processes (e.g. flow and sediment regimes, biogeochemical cycling, biodiversity, fisheries, human populations). In addition, trading off multiple objectives for a large set of dams over whole-basin scales is computationally challenging, as the required computational effort grows factorially with the number of dams and the number of objectives [47]. To illustrate the computational complexity, increasing the number of candidate dam sites in a hypothetical basin from 10 to 100 translates into increasing the number of potential dam portfolios that could be developed from 2^{10} (~1000) to 2^{100} (~10^{30}).

Approaches to find candidate dam portfolios need to address this large computational burden. In smaller rivers with fewer candidate dam sites, identifying a small number of practical portfolios might be feasible with local stakeholder inputs [48] (Figure 2b). In large basins, the complexity of the portfolio approach can be reduced by only including relevant dams in the analysis. For example, in the Se San, Se Kon, Sre Pok (“3S”) tributaries of the Mekong, 43 candidate sites were identified, yet only 17 had significant hydropower or impact, making the problem much more feasible computationally [29]. In large basins with many sites, techniques from operations research, such as genetic algorithms, can be deployed to find near-optimal combinations of sites without evaluating all possible portfolios [17,49]. Finally, dynamic programming algorithms have recently been developed to determine the full range of Pareto-optimal solutions with provable approximation guarantee in polynomial time [11,44,47,50,51]. All of these methods use a numerical model ('objective function’) to measure benefits and impacts for different portfolios to guide the selection of dam portfolios with favorable trade-offs (Figure 2c). The larger the focal area, the more daunting the data, modeling, and computational challenges. Thus, advances in high-performance computing and remotely sensed data acquisition hold great promise for addressing hydropower development with strategic planning across large and complex river basins [52,53].

Planning at scale

Large river basins often span many political jurisdictions, so the consequences of hydropower decisions extend across political boundaries. Accordingly, selecting sites for both building new dams [44,54] and removing existing ones to restore river connectivity [55] can be substantially improved by integrating information and planning across jurisdictions. For instance, dams in the Brazilian Amazon lowlands can interrupt the migratory route of ecologically and commercially important fish species that spend part of their lives in the estuary in Brazil but spawn thousands of kilometers upstream in the Bolivian, Peruvian, and Ecuadorian Andes [56]. Similarly, dam development in the Andean foothills can obstruct sediment and nutrient delivery to productive downstream ecosystems in the lowland Amazon [16,57]. Such transboundary impacts of dams built in one country upon its catchment neighbors are commonplace worldwide and can give rise to enormous political tensions.

The notion that the effectiveness of strategic hydropower planning increases with the spatial scale of planning is now supported by mounting quantitative evidence [44]. Because larger geographic domains offer more potential dam sites, more efficient portfolios are likely to emerge when planning scales are expanded. This can involve modest shifts from single to multiple sub-basins, or even exceeding watershed limits to encompass an entire country or region [30]. Unfortunately, the benefits of considering larger areas for dam placement must also be balanced against limited data on social and political feasibility [58]. Real-world complexity increases with the number of players and amount of data required [59], and the best portfolio of new dams across a large scale may include projects that are problematic in the locales where they are constructed. Thus, the most practical scales for selecting acceptable portfolios (Figure 3c), and hence a final portfolio for development (Figure 3d), will require balancing potentially conflicting ecosystem, political, and economic factors.

Several small dams or a single large one?

A long-standing question in aquatic conservation is if there is a generalizable rule as to whether multiple small dams in low-order tributaries are preferable to a single large mainstem dam. Evidence for individual criteria such as river network connectivity [38] and greenhouse gas emissions [11] suggest that multiple small dams in low-order tributaries cause less disruption per unit of electricity generated. As both tributaries and mainstem rivers in many basins are already highly altered [4], prioritizing conservation of less degraded tributaries and placing dams in sub-basins that are already dammed can be effective toward sustainability goals on a basin scale [17,60]. Yet from a financial perspective small dams may be more expensive to build; data from the International Renewable Energy Agency indicate that investment costs ($ per MW) of small dams (< 10 MW) are on average 25% higher than that of large hydropower plants [61]. Notably, however, large dams are systematically associated with high cost overruns [62]. Some studies have tackled the design problem associated with dam size and number of dams [63], but the excessive number of small dams can constrain strategic level multiobjective optimizations. While the literature on strategic hydropower planning has been expanding, it is challenging to prescribe a generalizable rule on whether many small or few large dams are preferable, because this depends on the objectives that are prioritized, the spatial distribution of ecosystem attributes across the basin, and where existing dams are already located.

Strategic planning under environmental change and uncertainty

Future dams will be confronted with unprecedented anthropogenic changes in the environment, with direct implications for the timing and rate of hydropower production [64]. For example, most dams proposed for the Amazon basin are likely to generate less hydroelectricity under future discharge regimes than what would be expected under historic baseline conditions [40,65]. Even in regions where overall hydroelectricity generation is not projected to change significantly under climate change, shifts in the frequency and timing of extreme weather events may require adaptations in dam design and operation rules [66]. Thus, incorporating future discharge regimes and coordinating dam operations will be key to mitigate the effects of climate change on future hydropower generation [40,65,67].

In addition to altering hydropower generation, changing discharge regimes will affect biophysical processes that determine the magnitude of certain environmental impacts from future dams. For example, precipitation and discharge regimes govern the erosion, transport, and deposition of sediments along a river continuum [68,69]. Similarly, the cycling of greenhouse gases, toxic metals, and nutrients such as phosphorus and nitrogen are affected by the seasonal fluctuation of reservoir water levels [70]. Many other ecosystem processes are directly linked to discharge regimes [71], and changing thermal regimes might alter the habitat distribution and vulnerability of fish [72,73]. If and how basin-scale manifestations of climate change impact the selection of optimal dam portfolios has not been explored in detail. Emerging results for the Mekong basin indicate that strategically planned dam portfolios will invariably lead to better trade-offs than site-by-site development under a wide range of future conditions [58]. However, more evidence is needed to quantify the direct effects of climate change on both hydropower generation and ecosystems, and thus how trade-offs for different portfolios manifest. Finally, robust decision-making approaches should consider uncertainties in social and institutional systems arising from climate change [32]. Filling these research gaps will help elucidate whether future scenarios of environmental change are associated with shifts in the identity of dams included in optimal solutions.

Implementation of selected dam portfolios

Once strategic assessments are carried out, how should a selected dam portfolio be implemented? Typically, energy demand grows steadily over time rather than in rapid jumps. This creates challenges for strategic selection of portfolios. As dams take many years — sometimes decades — to be built [62], selecting a dam portfolio will occur in anticipation of future demand. But demand for hydropower depends on highly variable socioeconomic development trends, especially in the face of ever cheaper alternative renewables [74].

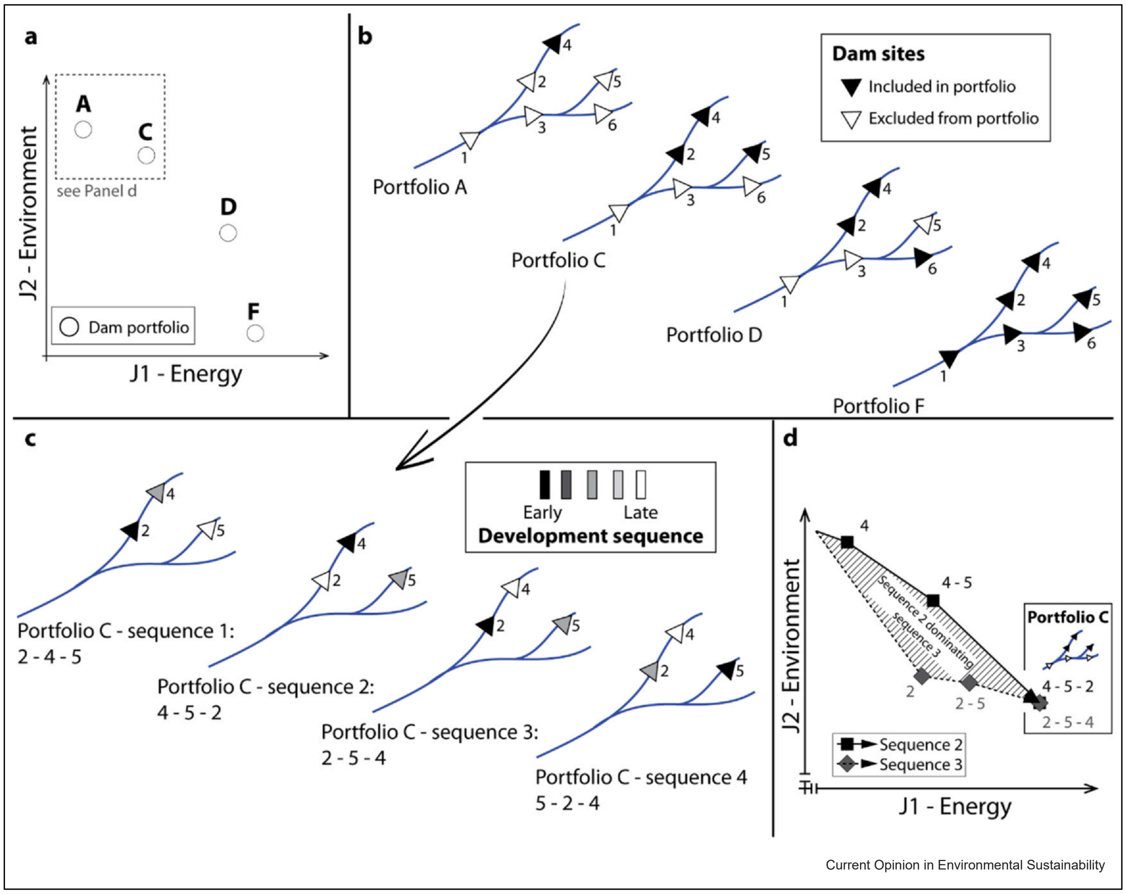
Even if stakeholders select an optimal dam portfolio to meet a specified hydropower target, there is an emerging no-regret problem: in which sequence should dams be built, so that stopping dam development before the full selected portfolio is built out still results in minimized trade-offs? Consider a scenario where stakeholders select a dam portfolio to meet an anticipated hydropower demand consisting of three dams (Figure 4a,b). This three-dam portfolio could be implemented in four different temporal sequences (Figure 4c). A worst-case scenario emerges when the dam site with the highest impact (dam #2) is selected first and, for any reason (e.g., investment in other renewables), the portfolio implementation is interrupted without full build out. In this scenario, the high impacts associated with that most detrimental dam are locked in (Figure 4d). A no-regret alternative would be to develop the portfolio of dam sites in a sequence that results in the most gradual realization of adverse impacts (Figure 4 c,d). To address this challenge, sequencing can be included as a direct objective in multiobjective optimization [75]. Alternatively, postprocessing of dam portfolios can yield probabilistic indicators for optimal dam sequencing: the more often a dam site is included in any dam portfolio, the earlier it should be developed [17]. Determining the full coverage of Pareto-optimal portfolios for all energy generation targets can be especially useful to address dam sequencing issues [11,44].

Integrating river basin and energy system planning

In real-world applications, strategic hydropower planning is not an isolated process. Rather, strategic hydropower planning needs to integrate with broader debates around greenhouse gas emissions and sustainable energy systems, which include alternative electricity sources. Thus, the question is: at what stage of energy planning — and how — should strategic spatial planning of hydropower dams be executed?

An ideal framework for the optimization of energy, water, and ecosystem services would combine power systems and river basin models, and jointly optimize the future energy generation mix with dam siting, dam design, and dam operation rules that fulfill grid-level electricity demand. While there are encouraging first

Figure 4



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Conceptualizing challenges for deriving an optimal dam sequence from strategically selected dam portfolios. A set of Pareto-optimal dam portfolios with increasing energy generation or installed capacity **(a)** does not necessarily form a practical dam sequence **(b)**. For example, portfolios C and D do not form a sequence, as they contain different dam sites (black triangles in b). Even within a certain portfolio (e.g. portfolio C), dam sites can be developed in different sequences **(c)**. The colors of triangles from black to white indicate if a dam is developed early or late. Over time, each of the sequences shown in c would result in a different temporal trajectory of trade-offs **(d)**. Notably, sequence 2, which builds small headwater dams first, results in lower impacts for intermediate levels of development compared to sequence 3, which builds the downstream-most dam first. While both sequences (2-5-4 and 4-5-2) result in the same final portfolio with the same trade-offs, sequence 2 creates a 'no-regret' strategy if dam development is terminated before all dams are built, as sequence 3 is dominated by sequence 2 (panel d).
Adapted from RJP Schmitt, et al. [17].

steps towards integrating models for power systems and hydropower operations [37,76], full integration of those models has yet to be mainstreamed. Recently, energy system models have started to be coupled with global climate models, but the consideration of a full range of environmental externalities is still deficient. Broadly used energy systems and capacity expansion models are beginning to include air pollution as an environmental externality [77–79]. However, energy system models often fail to include impacts on river functions and ecosystem services as external costs [80].

Integrating strategic energy and hydropower planning also implies a change in scales. With integration into broader energy systems planning, dam planning needs to encompass energy networks that may extend beyond river basin boundaries [37,81]. On smaller scales, the design and operation rules of an individual dam and the resulting environmental impacts can depend on which other dams will be developed in tandem, as well as the environmental objectives that are prioritized. For example, a joint optimization of design and operation of a Cambodian dam for better sediment flushing and fish passage reveals a wide range of trade-offs between environmental and economic objectives [82]. Thus, balancing trade-offs is key on both the portfolio and project level.

A practical alternative applied to integrate river basin planning with energy system models has been to determine hydropower demand from a broad energy systems perspective, constraining optimization to portfolios that meet such demand [30,34]. More advanced energy models can incorporate generation profiles of individual dams, thus allowing for the definition of boundary conditions for portfolio optimization that considers not only mean annual generation, but also hydropower supply during certain critical peak hours. These approaches can incorporate the role of hydropower in balancing intermittent renewable energy from solar and wind. An understanding of the need for back-up power supply options and the role of hydropower given seasonal fluctuations in electricity supply and demand will be on the frontier for new joint energy and river planning models.

Conclusion

Because of the connected nature of river networks, dams can create cumulative impacts that require assessment at the scale of the entire river basin. In this regard, strategic hydropower planning can support informed choices from the evaluation of a wide range of planning alternatives early in the decision process. Past years have seen a rapid proliferation of case studies highlighting the advantages of basin-wide strategic planning over project-level approaches. However, the actual creation of strategically selected portfolios of dams is rare, likely due to the challenges of coordinating across multiactor, multijurisdiction settings. Moving forward, real-world implementation of strategic hydropower planning, ideally integrated with energy systems planning, will be key toward low-impact renewable energy grids.

Declaration of Competing Interest

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

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