Global hydropower expansion without building new dams

Kayla Garrett¹, Ryan A McManamay¹,∗ and Jida Wang²

¹ Department of Environmental Science, Baylor University, Waco, TX, 76798, United States of America
² Department of Geography, Kansas State University, Manhattan, KS, 66506, United States of America
* Author to whom any correspondence should be addressed.

E-mail: Ryan_McManamay@baylor.edu

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Abstract

Reducing global carbon emissions will require large-scale transitions from fossil fuels to renewable energy resources. Hydropower will likely play a role in those transitions as it provides reliable energy storage while counter-balancing intermittent renewables. However, the construction of new dams comes at significant environmental costs to river ecosystems. An optimal future considers how to maximize the benefits of hydropower while minimizing environmental impact through revitalizing existing infrastructures. Herein, we quantify this potential using a spatially comprehensive global inventory of geolocated dams used for purposes other than hydropower, and augment these results with modelled estimates of small, unmapped dams. Furthermore, we examine increases in hydropower potential from efficiency upgrades at existing hydro-plants. These opportunities afford non-invasive increases in hydropower in populated areas neighbouring biodiversity hot spots. Overall, we estimate that these contributions could potentially provide up to a 9% increase to current global hydropower, potentially reducing the costs of construction and transmission, all while offsetting impacts to biodiversity and river ecosystems incurred by planned new hydropower construction.

1. Introduction

With global population expected to reach roughly 10 billion in 2050 (UNDESA 2017) and world energy demands doubling from 2018 (USEIA 2019), there are increasing concerns about how to meet global electrification goals without causing irreversible damage to ecosystems and communities. Fossil fuels have generally supported global development, providing 85% of total energy consumption and 63% of electricity production in 2019 (BP 2019). Of the total worldwide electricity production, hydropower comprises 17%, roughly half of the production from all nuclear and renewable sources (BP 2019). Hydropower continues to grow rapidly in developing countries seeking energy expansion while lowering carbon emissions from the energy sector.

As of 2014, an additional 3700 hydropower dams were either in planning or construction phases (Zarfl et al 2014), accounting for a 73% increase in the world’s hydropower capacity. This new phase of global dam construction could reduce the world’s large free-flowing rivers by 21%, and threaten the diverse fauna present in these ecosystems (Zarfl et al 2014, Winemiller et al 2016, Grill et al 2019). Recent studies also suggest that the increased prevalence of small hydropower (SHP) construction dominate river fragmentation and ecosystem impacts, in addition to that of large hydropower (LHP) (Couto et al 2021).

Widespread construction of new dam infrastructures could induce irreversible alterations to river ecosystems in some of the world’s most biodiverse ecosystems.

Resource assessments of renewable energy potential are commonly conducted at macro-scales to understand the technical feasibility of infrastructure development prior to large capital investments (e.g. Gernaat et al 2017). Most nationwide assessments, however, have predominantly focused on construction of new infrastructures (e.g. new dams), rather than investment in revitalizing existing infrastructure, potentially lessening economic and environmental costs (Szabó et al 2016, Chaudhari et al 2021). Many dams currently exist that serve a
societal purpose other than hydropower, and yet, their environmental impacts, specifically fragmentation (Grill et al. 2019), flood reduction (Fitzugh and Vogel 2011), water loss from evaporation (Friedrich et al. 2018, Zhao and Gao 2019), thermal alteration (Olden and Naiman 2010), and conversion of lotic to lentic systems, are already largely realized. These ‘non-powered dams’ (NPDs) are typically used for other purposes including irrigation, flood control, recreation, and water supply—but these infrastructures can be retrofitted for ‘run of river’ energy generation with less financial and environmental burden (Hadjerioua et al. 2012, Szabó et al. 2016). Although many hydropower dams are at the end of their designed life expectancy and face decommissioning, a multitude of other hydropower facilities have many years of continued operation with the potential for operational and infrastructural efficiency upgrades. Particularly, reoperation and installation of advanced turbine technologies could yield 3% or more increases per facility (DOE 2018). Our study sought to understand how much global hydropower energy capacity could be provided by this ‘low-hanging fruit’, without the construction of new dams.

Within this study, we explored potential increases in hydropower capacity derived from three sources—geographical mapping of NPDs, projections of unmapped (unobserved) NPDs, and efficiency upgrades to existing hydropower facilities. We then examined how these energy sources overlapped with regions of planned new LHP and SHP construction, as well as fish biodiversity hotspots, to determine if untapped hydropower resources can potentially offset some of the environmental burden of new development in these regions, with particular emphasis on the Amazon, Congo, and Mekong Basins. Technology and policy innovations in this realm of renewable energy encourage the forward motion of global development—without sacrificing ecosystems that we aim to protect.

2. Methods

2.1. Overview

Geographical mapping of dams relied on fusing multiple existing data repositories of cataloged dams and ensuring non-duplication and consistency among records. This inventory provided the basis for calculating site-specific estimates of energy potential from NPDs and existing hydropower upgrades; however, these databases exclude small dams, typically those with <0.1 MW of energy potential. To examine the potential for pico-hydropower potential, distribution modelling of unmapped dams is required (Coutos et al. 2021). Analogous to global lake mapping efforts (Downing et al. 2006, Lehner et al. 2011, Messager et al. 2016, Sheng et al. 2016), unmapped NPDs represent small dams that are expected to exist but lack spatial representation in the landscape due to limitations in remote sensing products and access to available inventories. Across regions, we then explore the potential magnitude of these new resources to displace or offset new construction of LHP and SHP development and ameliorate global aquatic biodiversity conflicts. The following methods are an abbreviated version of full details, which are provided in supporting information (available online at stacks.iop.org/ERL/16/114029/mmedia).

2.2. Global dam inventory (geographical mapping of dams)

The inventory and mapping effort compiled georeferenced dams from several repositories and identified structures constructed for non-powered purposes. This Global Dam Inventory (GDI) comes from a combination of sources in order to represent the most comprehensive datasets of dams across the world. The inventory includes the AQUASTAT database from the Food and Agriculture Organization (FAO 2013), the Global Reservoirs and Dams database (Lehner et al. 2011), and the Georeferenced global Dam And Reservoir dataset (GeoDAR) v1.0 beta (Wang et al. 2021). Each database has unique sources of information, but also varying levels of redundancy in lists of dams, which, at times, have varying nomenclature (supporting information). Records within the International Commission on Large Dams dataset (ICOLD) did not contain readily available georeferenced locations. The use of GeoDAR rectified the lack of spatial coordinates, and we were able to apply the georeferenced version that located ~40% of the ICOLD dams (or ~80% in reservoir storage capacity) (Wang et al. 2021). Information on dam height and mean annual river discharge was compiled from geospatial repositories (e.g. Grill et al. 2019) and web-scaping repositories of dam information, such as MW capacity for existing hydropower facilities (supporting information). In order to ensure consistent methodology across a global scale, regionally specific inventories were omitted. This was done because these detailed inventories are globally uncommon, and the goals of this paper favor pursuing a global scale, regionally consistent modeling approach. That being said, detailed regional inventories provide a validation of our global modeling approach.

To calculate potential hydropower capacity \(P\) for each mapped NPD and mapped hydropower dams without capacity information, we assumed a conservative efficiency \(n\) of 0.85 (Hadjerioua et al. 2012) in equation (1).

\[
P = \rho g h n Q\tag{1}
\]

where \(P\) is power (MW), \(\rho\) is the density of water (kg m\(^{-3}\)), \(g\) is gravitational acceleration (9.81 m s\(^{-1}\)), \(h\) is dam height (m), and \(Q\) is discharge (m\(^3\) s\(^{-1}\)). At each site, mean annual \(Q\) obtained from Grill et al. (2019) was adjusted to account for losses in
water availability from other human uses (supporting information). Despite accounting for human uses, mean flows may still overestimate generation capacity, whereas the 30th percentile $Q$ provides a more reasonable estimate of $P$ (Kao et al 2014). Given that flow percentiles were largely unavailable for the world, we used a previous hydropower assessment across climatic regions of the US (Kao et al 2014) to calculate an adjustment factor ($-0.227$) to apply to our calculation of $P$ to estimate capacity based on 30th percentile flows.

2.3. Unmapped NPDs

Frequencies of unmapped NPDs are largely motivated by work done in predicting the abundance and size distributions of the world’s lakes (Downing et al 2006, Seekell and Pace 2011, McDonald et al 2012, Cael and Seekell 2016). Studies on lake abundance have demonstrated that traditional remote sensing efforts only account for the larger and aerially observable waterbodies, but are missing crucial records of more abundant, yet smaller lakes and ponds (Downing 2006, Seekell and Pace 2011, McDonald 2012, Cael and Seekell 2016). In lake modelling, the Pareto distribution has been used to demonstrate the relationship of size and abundance—we apply the same principles to examine relationships between potential energy capacity (MW) and dam abundance. While the Pareto distribution accurately models mid- and large-range observations, it has been shown to overestimate small lake abundance (Seekell and Pace 2011, Cael and Seekell 2016) (supporting information).

Pareto distributions were developed for 15 different global regions, where estimated MW capacity of dams (both NPD and existing hydropower) was plotted against the frequency of occurrence (figure 1). We presume that observational frequencies of large, mapped facilities are comprehensive and accurate and can be used to develop models to predict the frequencies of unmapped dam occurrences. Using the distributions of observed facilities only, we developed both a Pareto power law relationship (equation (2)) and a tail corrected model curve (TCM) (equation (3)), which avoids overestimation in the lower range capacities. We expect the global abundance to exist between the two models. Regional hydropower summations were determined using area under the curve integration methods (supporting information). Variables $p$ and $n$ are the log transformed values for the threshold MW capacity and the corresponding frequency of dam occurrences at that threshold. Parameters $\alpha$, $\beta$, $\kappa$, $l$, and $m$ are shape and location values generated using the sum of least squares approach to minimize error (supporting information).

\[
\begin{align*}
  n &= \alpha p + \beta \\
  n &= \log_{10}(\kappa - p) + l - mp.
\end{align*}
\]

As a validation of our models, we compared the TCM to comprehensive dam datasets available for two regions: an assessment of NPDs within United States (Hadjerioua et al 2012) and the Brazilian database (ANA 2018). The TCM estimates were within 3% of the comprehensive inventory in the US NPD assessment ($\sim$53,000 dams), whereas the Pareto model predicts over three times current estimates of facilities $>0.01$ MW, as demonstrated in figure 1(a). The Brazil
2.4. Hydropower upgrades

Among renewables, the efficiency of hydropower turbines achieves the highest rates (DOE (Department of Energy) 2018); however, there is still room for growth in the older facilities, as technologies have advanced greatly since the hydropower resource was initially accessed (DOE (Department of Energy) 2018). Most hydropower turbines last roughly 50 years, at which point technological upgrades are required (DOE (Department of Energy) 2018). It is expected that by modernizing equipment, existing hydropower plants could see a 1%–3% increase in operation efficiency (DOE (Department of Energy) 2018).

Given lack of global databases on information regarding turbine upgrades, we presume all facilities constructed prior to 1970 had been upgraded at least once by 1970. We then distributed the 3% efficiency increases across the 1970–2020 period, based on the year of construction \(Y_{\text{upgrade}}\) for hydropower facilities. From this distribution, dams with last upgrades in 1970 received a potential efficiency upgrade of 3%, while facilities with initial year of operation as of 2020 are assumed to require no modernization. This conservatively provides a 0.06% potential increase in efficiency for each year of dam construction prior to 2020 (equation (4)). \(P_{\text{new}}\) represents the expected power output after upgrade based on current power \(P\) in MW.

\[
P_{\text{new}} = P \left[ 1 + \frac{0.03}{50} (2020 - Y_{\text{upgrade}}) \right]. \tag{4}
\]

2.5. Maximizing opportunities for untapped hydropower potential

To examine where new hydropower construction may be offset by infrastructure revitalization, potential capacity results for upgrades and NPDs were summarized for regions and compared with totals of planned new LHP projects (Zarfl et al 2014) and new SHP expansion estimates (Couto and Olden 2018, Coutos et al 2021). At the site-specific scale, we conducted a clustering procedure (supporting information) to compare the energy potential from NPDs and hydropower upgrades to that of planned LHP and rates of biodiversity. This yielded a matrix of scenarios for identifying which NPDs and upgrades offer the most advantageous opportunities to offset new construction, ameliorate energy poverty, and avoid biodiversity loss. Rates of biodiversity were determined using global drainage basins and fish species counts (Tedesco et al 2017).

Specifically for the Amazon, Mekong, and Congo Basins, we developed scenarios that would take advantage of new sources of hydropower potential to minimize the impacts of planned new hydropower development. Scenarios systematically considered how the MW capacity from NPDs and efficiency upgrades could replace individual facilities or groups of new hydropower facilities in those basins (Zarfl et al 2014) with the priority of replacing facilities impeding access to the main stem of the river and estuary (supporting information). Using more regionally specific fish species richness data specific for each basin (Winemiller et al 2016, IUCN 2020, Jezequel et al 2020), we estimated the total number of fish species that would benefit from scenarios offsetting new hydropower construction (supporting information). Additionally, we compared fish biodiversity levels between locations of NPDs and hydropower upgrades to locations of new planned hydropower development to show that infrastructure revitalization typically occurs in less biodiverse areas, further reducing environmental impacts.

2.6. Conducting a site-specific cost analysis of alternatives

To better understand the economic trade-offs that are present in making the decisions between NPD conversion/hydro-dam upgrades, removal, and new construction, a site-specific cost assessment was conducted across the GDI generated in this study. For cost estimates of NPDs, equation (5) was used, where ICC is initial capital cost in USD, \(P\) is design parameter capacity of the conversion in MW, and \(H\) is hydraulic head in ft (O’Connor et al 2015). To provide a basis for comparison of new construction cost of comparable power and height parameters, the cost of new stream-reach developments was considered against NPDs, as provided by equation (6) (O’Connor et al 2015). Equations (7) and (8) were used to provide scenarios for upgrade costs in existing hydropower facilities. These equations are demonstrative of the ICC as a function of the facilities rated power capacity \(P\) in MW (O’Connor et al 2015). The cost of unit additions projects is shown by equation (7), and the cost of generator rewind projects is shown in equation (8).

\[
\text{ICC} = 11\,489\,245P^{0.976}H^{-0.240} \tag{5}
\]

\[
\text{ICC} = 9\,605\,710P^{0.977}H^{-0.126} \tag{6}
\]

\[
\text{ICC} = 4\,163\,746P^{0.741} \tag{7}
\]

\[
\text{ICC} = 250\,147P^{0.817}. \tag{8}
\]

The cost of dam removal was determined using equation (9). Removal of dams increases exponentially with dam height, so this cost estimate is based on a log–log relationship (McManamay et al 2019). Here, \(C\) is cost of removal in USD and \(H\) is dam height in m.

\[
\log(C) = 2.29\log(H + 1) + 3.41. \tag{9}
\]
Equation (5) was applied only to the records in the GDI identified as NPDs, while equations (7) and (8) were separately applied to each site identified as a hydropower facility to represent two upgrade scenarios. Equation (6) was applied to all NPDs for their estimated MW capacity and existing height, whereas for hydropower facilities, it was applied to only consider the MW capacity gained from upgrades, not an entire new facility. Equation (9) was applied to all dams in the GDI. In addition, the equations were adjusted for inflation from 2015 (equations (5)-(8)) and from 2019 (equation (9)).

3. Results

After compiling the databases (supporting information), there were 20,574 dams identified as NPDs, and 8172 identified as hydropowered, for a total mapped set of 28,746 dams. Of those we identified, about 72% of mapped dams that do not include hydropower as a designated use. From our inventory and mapping effort, the majority of NPDs were used for irrigation (31%), other/unlisted (29%), water supply (17%), flood control (14%), recreation (8%), navigation (1%), and fish farming (<1%). In the GDI, 52% of hydropower facilities list hydropower as their only purpose. Across the remaining hydropower inventory, 22% of facilities had one additional purpose, 14% had two additional purposes, 8% had three additional purposes, and 4% had four or more additional purposes (SF.16).

Our estimates suggest that global hydropower capacity could be increased by roughly 78 GW, a 7%–9% increase in existing global hydropower capacity (figure 2, Web table 1). In general, we find that the largest source of potential hydropower growth comes from retrofitting mapped NPDs, followed by addressing facility upgrades (figure 2(a)). Unmapped estimates constitute the smallest growth potential globally (figure 2(b)) but remain significant in a regionally specific assessment. In addressing future construction regional assessments suggest that significant portions, and in some cases all, of SHP or LHP planned capacity could be replaced by the proposed alternative sources (figure 2(c)). If alternatives to new construction were pursued globally, this looks like reducing the planned capacity for SHP or LHP by 10% or 11% respectively (figure 2(d)).

3.1. Global mapping of NPDs

Based on known locations of NPDs, 60 GW of power could be produced from retrofitting existing dams with generation facilities. Many of these opportunities would come from small scale (i.e. micro- or pico-) hydropower facilities, which are highly beneficial for rural areas that have unreliable continuous grid operations (Szabó et al. 2016). However, more than 3000 NPDs are larger than 1 MW in terms of potential hydropower capacity, which can provide a comparable global scale commodity to offset some of the new construction plants previously identified (Zarfl et al. 2014, Couto et al. 2018). Figure 3(a), depicts the locations and magnitudes of energy capacity for NPD conversion, which may provide regional relief from the burdens of new hydropower construction projects planned for the near future. Situations of high-low clusters (high NPD MW, low new hydropower MW) were least numerous and are scattered globally yet could provide potential opportunities for addressing energy poverty (figure 3(a)). Similarly, areas of achieving high NPD energy in areas of low biodiversity conflict are less numerous than other scenarios but pose optimal solutions for many countries to increase their renewable energy portfolio (figure 3(b)). In general, the results of the clustering suggest little regional aggregation or generalization of optimal energy solutions; the best opportunities for alternatives to new construction are site specific, and instances of ideal direct replacement are rare. In addition, figure 3(c) demonstrates the additional expected MW capacity of each country based on the proposed projects identified by Zarfl et al (2014). NPDs with a main purpose of unlisted/other constitute 43% of hydropower MW potential, followed by navigation providing 21% and irrigation providing 18%. The remaining purposes of recreation, flood control, and water supply provided the remaining capacity (SF.17).

3.2. Unmapped potential from smaller NPDs

When applied to all regions, the TCM and Pareto models yielded 500–2100 MW of potential NPD retrofit resource (figures 2(a) and (b), Web table 1). While these values seem small compared to the 68 GW capacity from the mapped NPD inventory, the context of their application is significant in rural developing regions. This may still be a conservative estimate in small dam occurrences, as the United States and Brazil validation cases show—where regionally specific data generates a higher density of pico-hydro potential.

3.3. Existing hydro-dam upgrades

Based on applying estimates of upgrade potential based on ages of facilities, an additional 17 GW of power could be gained (figures 2(a) and (b), Web table 1). Similar to the narrative for NPDs, utilizing upgrades to offset new construction is best assessed at a site-specific level to provide regional alternatives to LHP (figure 3(b)) or to minimize biodiversity losses (figure 4(b)). This may still serve as a lower end estimate to improvements from modernization, as some cases may experience up to 10% efficiency increase (DOE (Department of Energy) 2018).

3.4. Amazon, Mekong, and Congo case studies

When assessing the overlap of alternative hydropower growth from NPDs and upgrades to global
biodiversity (figures 4(a) and (b)), there is again a rarity in occurrences of high MW capacity alternatives and low biodiversity—although a few clusters of NPDs in Brazil and southeast Asia look promising (figure 4(a)). Addressing hotspot regions of biodiversity (figure 4(c)) and utilizing the existing infrastructure in the more urbanized regions, produces more applicable results, as opposed to generalizing large basins.

In the three case studies addressing hydropower development in the Amazon, Congo, and Mekong River basin, both the Amazon and Mekong presented opportunities for alternatives to new development (figure 5). In the Amazon, 17 new projects could be avoided near the delta by utilizing 1600 MW of potential NPD and upgrade capacity in the country of Brazil alone (figure 5(a)). Approximately 54% of the basin could remain open and free flowing alternatives actions are taken (figure 5(d)). For this basin, 350 species impacted could decrease to 60 by utilizing infrastructure in already highly urbanized and impacted areas as opposed to new development.

In the Mekong, 100% of the basin could possibly remain unaltered by utilizing the NPDs and facility upgrades of existing hydropower plants in the surrounding countryside (figure 5(c)). In fact, the 40,000 MW of planned new capacity, all within the Mekong Basin, is potentially replaceable by nearly 80,000 MW of alternative hydropower capacity in the surrounding countryside. These results suggest biodiversity impacts decrease from 195 species down to 90 in this region (figure 5(e)).

Unfortunately, the Congo River Basin will continue to be affected by new development, as planned projects are of an order of magnitude that exceeds the current possibility of offset (figure 5(b)). While it may be too late to mitigate harm from the larger of these two projects (44,000 MW), the surrounding dams from the basin could provide 95% of the capacity for the remaining 350 MW facility. The larger of the two dams remains a serious threat to the rivers structure and biodiversity, as this area is reported to house over 170 freshwater fish species.

3.5. Cost analysis

For NPD conversion cost versus removal, three scenarios were conducted (figure 6(a)). Scenario 1 represents the global cost for converting all 20,574 NPDs for hydropower generation. This cost is totalled at $238.3 billion USD. Scenario 2 includes the cost of
removing all NPDs globally, for a total of $169.5 billion USD. Scenario 3 represents the comparable cost of new hydropower construction for the same MW output as the entire NPD conversion potential. This cost comes to $332.5 billion USD.

The cost analysis for hydropower dam upgrades included a total of four scenarios, as there are two calculated options for upgrade potential (figure 6(c)). Scenario 1 represents the global cost of conducting a generator rewind project on all hydropower facilities identified in the GDI. This cost would total $74.6 billion USD. Scenario 2 considers the possibility of unit additions to all existing hydropower facilities at a total cost of $783 billion USD. Scenario 3 considers the cost of removing all hydropower facilities for $334.7 billion USD. The final scenario takes the MW total of upgrades alone to facilities and applies that MW value to a new-stream development to determine a
Figure 4. Clustering of NPDs and upgrades compared to biodiversity. Based on clustering of NPDs (a) and existing facility upgrades (b) to species richness data, a replacement matrix was generated. For example, dams with a large potential MW capacity/upgrade that correspond with areas of low biodiversity classify as high–low (areas of decreased impact on species). The global basin species richness is also summarized (c).

comparable cost. This cost comes to $95.4 billion USD.

4. Discussion

4.1. Easing the burden of sustainability
At least 860 million people still do not have access to electricity, with a majority residing in Sub Saharan Africa (IEA 2019). As energy demands rise, continued development of new dams and hydropower facilities pose a threat to the few remaining free-flowing rivers. While there are fewer constructed dams in countries with low Human Development Index values, of the existing dams in these countries, between 80% and 87% are identified as NPDs (UNDP 2019). Although dependance on hydropower may lead to a certain vulnerability in the face of climate change, utilizing this existing infrastructure provides a potential ease on
immediate development burdens and hurdles—such as energy storage. These regions of rapid future development pose challenges and opportunities to meet growing socioeconomic needs with minimalistic, efficient, and environmentally benign energy alternatives, particularly increasing hydropower without constructing new dams.

As movement towards sustainable development across the globe grows, so does the concern for the pathways in which societies attain those objectives (O’Neil et al 2017). The cost of one global sustainable practice, particularly carbon emission reductions, should not occur at the expense of other practices, such as biodiversity conservation. A growing number of studies suggest that continued new hydropower development will jeopardize the world’s remaining free-flowing rivers, particularly in biodiversity hotspots (Winemiller et al 2016, Grill et al 2019, He et al 2019, Couto et al 2021); however, many studies fail to identify viable energy alternatives, namely displacing fossil resources with dispatchable, non-itermittent renewable resources. Our results suggest there is fertile ground for optimizing societal benefits that could be gained through existing infrastructure revitalization. Life cycle assessments for hydropower demonstrate that nearly 90% of the environmental impacts incurred by new projects is during the material manufacturing and construction phases (Wang et al 2019). Rather than introducing new infrastructure, approaching the efficiency of the existing system offers a carbon neutral and lower monetary investment towards increasing total generation (Granade et al 2009, Wang et al 2019). In new ‘greenfield facilities’, as much as 70% of the total cost of in 2016 came from construction alone (Szabó et al 2016).
4.2. Understanding the trade-offs

Seeking to improve environmental systems in a world of increasing energy demand will inherently require assessments of trade-offs and understanding the implications behind pursuing one technological pathway over another. The authors do not wish to
convey the idea that pursuing NPD retrofitting and facility upgrades is the only option, nor necessarily always the best option in the complex network of ecology, energy, and economics. We do, however, suggest that global-scale, macroscopic inventories of resource potential are needed to understand whether a given technological pathway is even theoretically possible, including the potential to mitigate or even improve existing environmental conditions.

In the context of improving environmental quality and preserving biodiversity, one proposed action is dam removal. Aging infrastructures that have exceeded their life expectancy and fail to continually serve their societal purpose could be slated for removal. However, not all instances of barrier removal provide a net benefit to the system, despite efforts to increase river connectivity (King et al 2017, McManamay et al 2019). For instance, solar and wind technologies are considered viable options for replacing hydropower electricity and reducing dependence on water sources (He et al 2019); however, in humid areas, deforestation associated with solar development is estimated to result in a net reduction in carbon sequestration (De Marco et al 2014). Furthermore, in the absence of grid-scale storage options, lost hydropower energy resources would likely be replaced with fossil sources in areas where solar and wind intermittency results in grid instability.

Avoiding dam construction reduces a significant portion of ecological and physical alterations of river ecosystems (Hadjerioua et al 2012, Szabó et al 2016, McManamay et al 2019, Wang et al 2019). The addition of turbines to NPDs does not come without environmental risks, such as fish impingement on turbines and terrestrial impacts from transmission infrastructure (Barnthouse 2013). However, hydropower entrainment, turbine strike injury, and mortality estimates can be decreased by deploying turbines with low-impact designs (Bevelhimer et al 2019). In many regions of the world, environmental regulations and monitoring requirements for hydropower facilities are far more stringent when compared to dams and reservoirs used for other purposes (IHA 2018, UN 2018, FERC 2020). In some cases, the addition of power to a dam elicits environmental policies, standards, and regulations that would otherwise be unavailable, such as providing opportunities for improved monitoring (USEPA 2005). The addition of turbines with aeration technologies have also been shown to improved water quality, i.e. low dissolved oxygen, in many cases (Cook et al 2003, Sullivan et al 2006).

The physical footprint of a powerhouse and transmission facilities remains a potential concern and should require careful and intentional planning. NPDs and existing facilities, however, are often already located proximate to populated areas, further lessening the environmental and economic burdens of new transmission construction (Szabó et al 2016). In the case of NPDs, the intended and original uses of these facilities are already well assumed to be meeting the needs of the community, and would remain the primary function (Witt et al 2018). Increase in hydropower potential at existing hydropower facilities calls for no new development, but rather an integrated systems design overhaul. Technology for computer-aided analysis of flow and operations, turbine optimization, and computerized control modules provide support in optimizing facilities operational costs and generation capabilities (Ahmad et al 2020). However, in these cases, aside from operational and technological limitations, sedimentation and increasing hydrologic variability continue to pose restraints to achieving optimized operational conditions (Wisser et al 2013).

In the cost analysis conducted in this study, several different scenarios can be played out with varying economic, social, and ecological benefit. Obviously scenarios that pursue removal of dams must consider the loss in value of the purpose that dam currently provides for either NPD or hydropower. Additionally, there are other costs not assumed by this coarse assessment, and the cost of removal utilized herein may be an under-estimate. Other considerations such as mitigation and other planning aspects of a full decommissioning will incur additional cost. In these cases the entirety of the net cost-to-benefit ratio is more nuanced, and explored more thoroughly in other publications (ex. Bonnet et al 2015, McManamay et al 2019, 2021). When NPDs are compared at a site by site level of conversion versus new construction, new constructions costs represent the most expensive scenario. It is here that NPD conversions provide a desirable economic alternative to new construction. In addition, NPD projects pose less threat to the surrounding ecosystems. Virtually all instances of site-to-site comparison yield that conversion is more economical than new construction for the same MW output.

Across the United States there is a wide range of arrangements for hydropower facilities, in capacity, reservoir size, and the multipurpose nature. In fact, the benefit of hydropower to a multipurpose dam varies as a function of not only capacity, but number of purposes (Bonnet et al 2015). As a dam includes more purposes, the total value to society increases and hydropower represents a smaller portion of the total value (Bonnet et al 2015). Over 50% of hydropower facilities in the GDI list no other purpose besides hydropower (SE16) although multipurpose projects contribute more to society as a whole. This lends to support that adding hydropower to NPDs can provide opportunity for expanded societal benefit. The multipurpose nature of hydropower facilities and the synergy of having multipurpose operations is well established across the US and is being used to inform NPD conversions across the country. For example, 40 NPD projects between 2006 and
2016 added considerable capacity to the United States hydropower fleet (Uria-Martinez et al. 2018). In addition to NPD conversions, many United States facilities sought to increase their capacity through facility upgrades. The Northwest region of the United States added approximately 800 MW of hydropower capacity from upgrades to the existing fleet (Uria-Martinez et al. 2018). In many cases, converting NPDs and upgrading existing hydropower facilities proves to be an economically feasible alternative with added value to society, as well as helping to alleviate the burden that new development could pose to environmental systems.

4.3. Ameliorating biodiversity conflicts with untapped hydropower resources in the Amazon, Mekong, and Congo
A vast body of literature suggests that the construction of new dams elicits measurable, significant, and, at times, irreversible, changes to the related ecosystems. The tradeoffs of energy, economics, and environment are under higher scrutiny as institutions seek to preserve biodiversity and maximize fruitful hydropower investments (Zarfl et al. 2014, Winemiller et al. 2016, Grill et al. 2019, Barbarossa et al. 2020). In some cases, the new construction projects in these key basins may be highly carbon intensive, placing further strain on ecosystems and overarching emissions goals (Räsänen et al. 2018, Almeida et al. 2019). The Amazon River Basin (figure 5(a)) has nearly 300 new dams under construction or planned for the coming future. There are multiple new dams planned at the delta of the Amazon River which pose a serious threat to river continuity, biodiversity, and material transport. Many of these planned facilities would be unnecessary, if development of NPDs and facility upgrades were adopted in Brazil; these existing dams are also more proximate to urban centers lessening the transmission cost burdens. In the Mekong Basin, all planned construction could possibly be avoided by utilizing infrastructure in the surrounding countryside where the ecological impacts are largely already realized. Unfortunately, in the delta of the Congo River Basin, there are two large scale dam constructions planned, one of which is among the world’s largest hydropower facilities and unparalleled in comparison to existing infrastructures (figure 5(b)). In all of these cases, new dams would pose significant threat to diadromous or potamodromous fish that migrate significant distances to carry out their life history requirements, as well as sensitive riparian floodplain communities (Barbatossa et al. 2020). Avoiding these new construction projects could allow large portions of these keys basins to remain free-flowing, as well as impact a smaller population of fish species.

The narratives of these three major river basins elicit a need for continued search for alternatives to invasive hydropower construction, particularly in regions of such global importance. Not all of the new planned construction may be avoided, but with more strategic planning, there are solutions and alternatives to increasing hydropower capacity. Our mapping suggests that more densely populated areas with growing energy demands coincide with the existing resource alternatives for hydropower, where the existing infrastructure is not only a better environmental advantage, but also significantly closer to urban centers, therefore decreasing transmission and distribution costs (Winemiller et al. 2016).

5. Conclusion

Improvements to mapping of global dams are needed to continue to develop an understanding of the complete potential resource that is available for alternative strategies for new hydropower development. The 2019 International Hydropower Association reported 25% more existing global hydropower capacity than estimated by our geospatial inventory and mapping effort. This difference primarily comes from inaccurate geospatial data in the East and Central Asian region. Although this can be adjusted for, it is demonstrative of inaccuracies in data availability, which will continue to hinder future efforts in understanding global hydropower potential. Additionally, our assessment is likely an underestimate of the potential from efficiency upgrades. Refining these estimates requires comprehensive information on dam characteristics, such as hydraulic head, flow, purpose, and when applicable, facility capacity (Wang et al. 2021). The consequences of limited spatial inventories of global dams remains significant. Aside from the greater societal awareness of untapped sources of renewable energy, unmapped dams continue to covetly fragment and alter the state of the world rivers at a global scale, and as such, accurate research on the cumulative ecological effects of these impoundments and barriers will remain lacking (Lehner et al. 2011, Couto and Olden 2018, Couto et al. 2021). The hydrologic assessment in this study assumes consistent recent past climatic conditions and is not based on future projections. The future implications of increased variability in global hydrologic trends, both temporally and spatially, will continue to affect uncertainties in the global water balance. As society seeks to mitigate global anthropogenic impacts, such as climate change and atmospheric carbon levels, these pursuits should not come at the expense of other dimensions of sustainability. Tradeoffs in environmental impacts among development goals are apparent, and yet to be fully realized (Thacker et al. 2019); hence, there is a great need for identifying optimal infrastructures of the future, including renewable energy alternatives (Wang et al. 2019). Minimalistic approaches harnessing the power-potential from existing dams where the environmental and financial costs have largely been incurred, provides a win-win
scenario for energy development, environmental preservation, and economic feasibility.

**Data availability statement**

The data that support the findings of this study are available upon reasonable request from the authors.

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**ORCID iDs**

Ryan A McManamay [https://orcid.org/0000-0002-5551-3140](https://orcid.org/0000-0002-5551-3140)

Jida Wang [https://orcid.org/0000-0003-3548-8918](https://orcid.org/0000-0003-3548-8918)

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