

A global-scale framework for hydropower development incorporating strict environmental constraints

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The benefits of developing the world's hydropower potential are intensely debated when considering the need to avoid or minimize environmental impacts. However, estimates of global unused profitable hydropower potential with strict environmental constraints have rarely been reported. In this study we performed a global assessment of the unused profitable hydropower potential by developing a unified framework that identifies a subset of hydropower station locations with reduced environmental impacts on the network of 2.89 million rivers worldwide. We found that the global unused profitable hydropower potential is 5.27 PWh yr⁻¹, two-thirds of which is distributed across the Himalayas. Africa's unused profitable hydropower is 0.60 PWh yr⁻¹, four times larger than its developed hydropower. By contrast, Europe's hydropower potential is extremely exploited. The estimates, derived from a consistent and transparent framework, are useful for formulating national hydropower development strategies.

The development of renewable energy (hydropower, wind power and photovoltaic power) is increasingly recognized as a crucial step in mitigating global climate change by reducing reliance on fossil fuels¹. Hydropower, in particular, offers a relatively cost-effective energy

source that can meet peaks in energy demand on grids with high penetrations of intermittent wind and solar energy^{2,3}. Currently, hydropower contributes 16% of the world's electricity and 69% of all renewable electricity⁴. Looking ahead, hydropower is expected to play a key role in the

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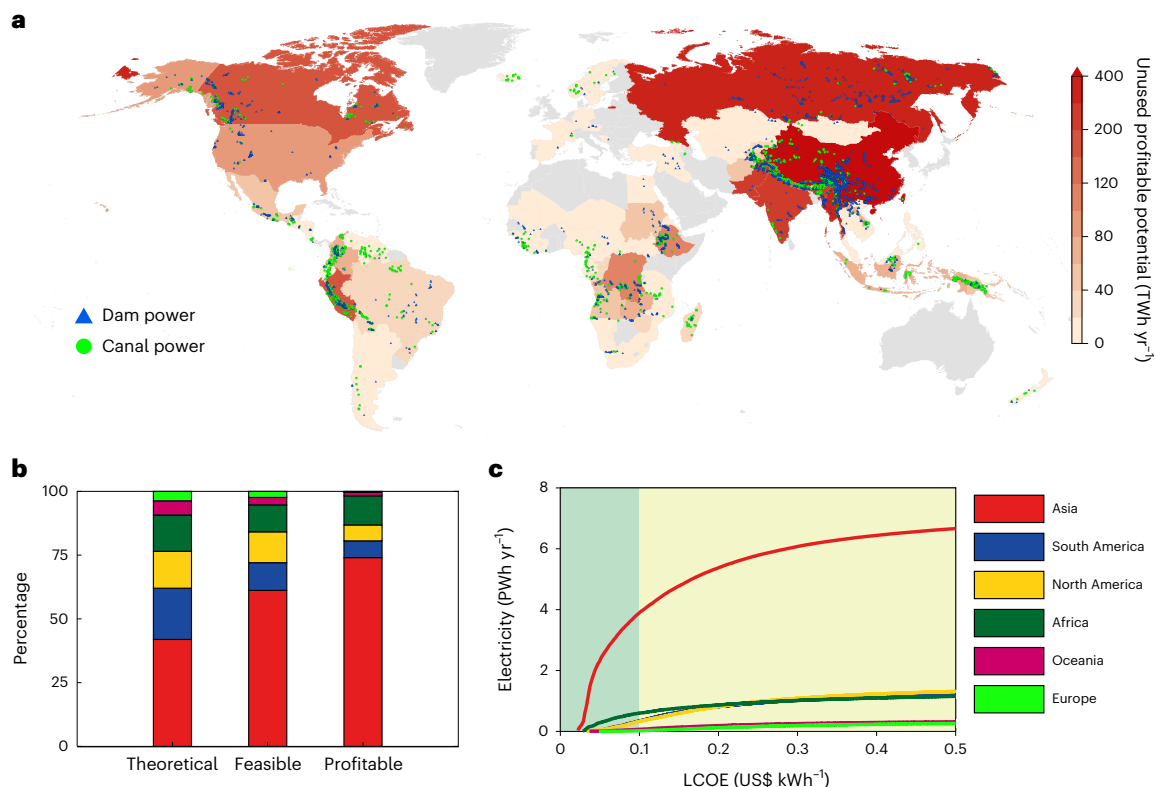


Fig. 1 | Spatial distribution and cost–supply curves of unused profitable potential at the global and continental scales. a, Spatial distribution of unused profitable potential. The profitable potential of each country was calculated on the basis of hydropower plant location. **b**, Proportion of theoretical, feasible and profitable potential for each continent. The feasible and profitable potentials

take into account environmental constraints. **c**, Cost–supply curves of unused profitable potential for each continent. The LCOE is less than 0.1 USD kWh^{-1} , we define the annual average electricity generation of the hydropower plant as the profitable potential.⁶⁷

transition of some nations to decarbonized energy systems. However, the future of global hydropower development is controversial because hydropower systems have many documented negative environmental and societal implications⁵, including the disruption of river ecosystem structure and functioning, the obstruction of fish migration routes, the release of greenhouse gases from reservoirs, exacerbation of flood risk via dam failure, land degradation during construction, social displacement and geopolitical issues^{6–8}. For global society to meet the sustainable development goals (SDGs) by 2030 (in particular, SDGs 6, 7, 9 and 13), a unified assessment of global unused profitable hydropower potential that incorporates constraints to reduce environmental and societal impacts is essential.

Previous quantitative studies have estimated that the global theoretical hydropower potential ranges from 30.67 to $127.58 \text{ PWh yr}^{-1}$ (refs. 9–13). Quantifying the unused, economically viable hydropower potential that minimizes some of the associated environmental impacts is challenging, with the wide range of previous estimates encumbered by (1) low spatiotemporal resolution of hydrological models, (2) the use of coarse river network maps that do not accurately represent river planform geometry and associated environmental conditions, (3) the lack of verification of sufficient river discharge gauge observations, and (4) incomplete databases listing existing global dams, reservoirs and hydropower plants. Consequently, the locations where new hydropower plants can be built in the future and their associated electricity production potential are not fully understood.

Concerning the sustainability of hydroelectricity, previous estimates have rarely incorporated restrictions that limit many negative impacts of hydropower plant construction¹⁴. For example, the most

up-to-date estimates made by Gernaat et al.¹² partially considered the environmental costs of hydropower development by incorporating the World Database of Protected Areas (WDPA), but excluded important factors such as tropical forests, peatlands and biodiversity from consideration. Additionally, environmental flow restrictions need to be considered in greater detail given recent calls for more coherent, multi-objective planning when developing new hydropower infrastructure¹⁵. Also important is the consideration of non-hydropower dams that can be converted to generate hydroelectricity, as well as the upgrading of existing hydropower dams to maximize their full potential^{16,17}. These relatively quick modifications would reduce environmental issues compared with developing new plants. However, as hydropower generation requires high water flow and a hydraulic head, it is unclear whether refurbishing non-powered dams is either economically or practically possible.

With the vision of developing the global unused hydropower potential sustainably^{18–20}, we performed a comprehensive analysis by synthesizing fine-resolution river discharge estimates, published reservoir/dam locations, demographic variables, environmental datasets, cost considerations and strict criteria to limit environmental and social impacts. The analysis was based on the reconstruction of global naturalized river flows in 2.89 million rivers worldwide (covering 60°S to 90°N , excluding Greenland)²¹ to determine locations where new hydropower plants could be established. The discharge dataset was comprehensively evaluated against the daily and monthly flow records of over 14,000 hydrological stations (Supplementary Fig. 1). For this virtual network, we considered the same two main hydropower systems¹², impoundment (having dams and reservoir) and diversion (having an

intake and downstream electricity generation unit), considering their different design criteria and variable impacts on the environment. We used the latest global high-resolution Multi-Error-Removed Improved Terrain digital elevation model (MERIT DEM; 3" resolution) and levelized cost of energy (LCOE) calculations (see Methods and Supplementary Fig. 2) to determine the optimal type and size of hydropower system at each potential site in the network.

To avoid sensitive locations, we applied strict criteria to limit environmental and social impacts. For example, we directly excluded hydropower plant development in heritage areas, biodiversity hotspots, forests, peatlands, earthquake-prone zones, densely populated areas and locations where dams/reservoirs already exist. To generate a more complete reservoir dataset that includes data for all installed hydropower plants worldwide, we integrated global reservoir datasets (for example, OpenStreetMap (ref. 22), the Global Reservoir and Dam Database (GRanD; ref. 23), the Global Georeferenced Database of Dams (GOODD; ref. 24) and the Georeferenced global dam and reservoir (GeoDAR) dataset (ref. 25)) and included a total of 445,669 reservoirs in our assessment (see Methods). Importantly, we stipulated that a new hydropower station must maintain an environmental flow that will support downstream river ecosystem integrity and water availability during baseflow conditions, particularly in dry seasons. In cases where sites identified for hydropower expansion are too closely situated, we retained the one with the lowest LCOE (see Methods; Supplementary Fig. 2). Collectively, this approach has allowed us to estimate the unused feasible and profitable hydropower potential worldwide (for definitions, see Supplementary Table 1 and Supplementary Fig. 2). Finally, we identified 124,761 unused feasible hydropower system sites worldwide, among which 4,644 sites are profitable (see Methods).

Our assessment reveals that the baseline global theoretical hydropower potential is 57.9 PWh yr⁻¹ (Supplementary Fig. 3 and Supplementary Text 1), slightly higher than the two most recent estimates of 50–52 PWh yr⁻¹ (refs. 12,13). We estimate the global unused feasible and profitable hydropower potential to be 10.89 and 5.27 PWh yr⁻¹, respectively. The global profitable hydropower potential shows an upward trend, with an annual increase of 0.008 PWh yr⁻¹ from 1979 to 2016 (Supplementary Fig. 4). However, the spatial distribution of global hydropower profitable potential trends is different. The profitable potential in Canada, Russia, the Andes, southern Africa, Indonesia and Papua New Guinea has increased over the past 40 years, while the profitable potential in the western United States, Europe and Central Africa has decreased (Supplementary Fig. 5). Furthermore, future climate change could increase or decrease hydropower production through changes in precipitation, evaporation, glacier melt, sediment load and extreme cascading hazards, but these changes and their impacts on the global profitable hydropower potential are extremely challenging to quantify^{26,27}. Regional power grid interconnection could mitigate climate impacts on hydropower²⁸. Thus, future studies and hydropower policy development also need to address climate change impacts on a case-by-case basis.

According to our analysis, impoundment power plants account for 81% of the global unused profitable potential, compared with 19% for diversion hydropower plants. The multiyear mean discharge at most impoundment power plants ranges between 100 and 1,200 m³ s⁻¹, compared with 10 to 150 m³ s⁻¹ for diversion plants (Supplementary Fig. 6). Most of these hydropower systems identified in our analysis have installed capacities of between 100 and 650 MW, but some have capacities of less than 50 MW (Supplementary Fig. 7). Few small plants were identified in our approach because they were not cost-effective (high LCOE), could not be designed to ensure that sufficient environmental flows could be maintained or they would have encroached on sensitive areas, particularly forests. Small diversion hydropower plants on tributary streams in the Himalayas and the Andes are appropriate because the steep relief allows sufficient fall heights to generate electricity efficiently. Contrary to the ongoing development in, for

Table 1 | The national theoretical, unused feasible and unused profitable potentials, and the ratio of unused profitable potential to the total electricity generation (P/T) in the main hydropower countries

Country	Theoretical potential (TWh yr ⁻¹)	Unused potential (TWh yr ⁻¹)		P/T
		Feasible	Profitable	
China	8,452 (14.6)	3,068 (28.2)	2,249 (42.7)	0.30
Myanmar	1,092 (1.9)	495 (4.5)	338 (6.4)	13.75
Russia	4,859 (8.4)	1,052 (9.7)	330 (6.3)	0.30
India	2,171 (3.8)	552 (5.1)	294 (5.6)	0.19
Pakistan	771 (1.3)	272 (2.5)	214 (4.1)	1.44
Canada	3,881 (6.7)	559 (5.1)	181 (3.4)	0.28
Peru	2,277 (3.9)	353 (3.2)	171 (3.2)	3.11
Nepal	729 (1.3)	212 (1.9)	144 (2.7)	29.22
D. R. Congo	2,124 (3.7)	179 (1.6)	119 (2.3)	11.28
Ethiopia	826 (1.4)	200 (1.8)	115 (2.2)	8.48
United States	3,056 (5.3)	441 (4)	89 (1.7)	0.02
Laos	412 (0.7)	137 (1.3)	74 (1.4)	2.14
Zambia	284 (0.5)	86 (0.8)	70 (1.3)	4.31
Colombia	2,146 (3.7)	200 (1.8)	67 (1.3)	0.84
Indonesia	2,700 (4.7)	258 (2.4)	66 (1.2)	0.23
Afghanistan	421 (0.7)	116 (1.1)	56 (1.1)	10.16
P. N. Guinea	1,455 (2.5)	167 (1.5)	54 (1.0)	16.75
Tajikistan	317 (0.5)	90 (0.8)	52 (1.0)	2.64
Angola	436 (0.8)	88 (0.8)	46 (0.9)	3.89
Mexico	840 (1.5)	214 (2.0)	45 (0.9)	0.13

P/T ratio exceeding one indicates that the country's unused profitable hydropower could fully satisfy total energy demand. Listed are the top 20 countries with unused profitable hydropower potential. The numbers in parentheses represent the percentage of the world's total potential. D. R. Congo, Democratic Republic of the Congo; P. N. Guinea, Papua New Guinea.

example, Vietnam, our analysis does not support small diversion plant development on tiny headwater streams because of their impact on the economic costs. Our analysis, however, does indicate that Iceland, Norway and Papua New Guinea could also potentially support profitable networks of diversion hydropower systems (Fig. 1a).

Our assessment is quite different from that of Gernaat et al.¹² due to the enhanced level of environmental constraints, our identification of substantially more existing dams and/or reservoirs, and more accurate discharge datasets to inform modelling. Notably, Asia's unused profitable potential (3.90 PWh yr⁻¹) is three times greater than the previous estimate¹⁰. While the spatial distribution of unused profitable hydropower sites in high-mountain Asia is roughly consistent with the previous assessment, the energy production cost is much lower in the high-relief Himalayas than in other parts of the world (Fig. 1c), leading to our finding of a greater profitable potential than was estimated before. Africa ranks second with a total of 0.60 PWh yr⁻¹ unused profitable hydropower potential. Together, Asia and Africa account for 85% of the global unused profitable potential (Fig. 1b), mostly in China, Myanmar, India, Pakistan and Nepal in Asia, and in the Democratic Republic of the Congo, Ethiopia and Zambia in Africa (Table 1 and Supplementary Table 2). North and South America, which have similar cost–supply curves, have unused profitable potential of 0.33 and 0.34 PWh yr⁻¹, respectively. South America has high theoretical hydropower generation potential, but our requirement to conserve tropical forest reduces both the feasible and profitable potential values greatly²⁹. Therefore, our estimate for South America's unused profitable potential is less

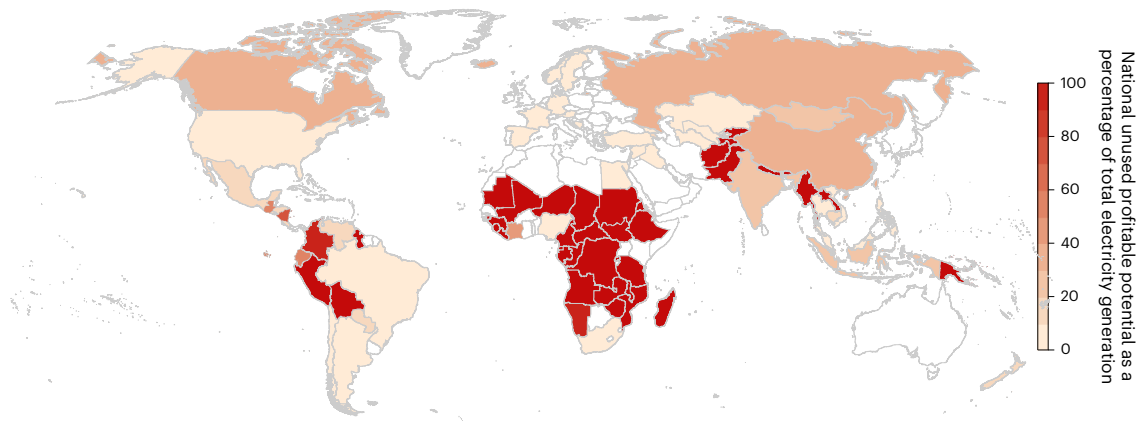


Fig. 2 | National unused profitable potential as a percentage of total electricity generation. The red areas represent the ratio of national unused profitable hydropower potential to total electricity generation. The dark red area represents a country that could potentially fully meet its current electricity demand by developing its unused hydropower potential.

than half that of Gernaat et al.¹², which did not consider the conservation of tropical forests. Oceania and Europe have limited unused profitable potential (Fig. 1c). We further found that Europe's unused profitable potential is only one-seventh that estimated by Gernaat et al.¹², largely because we imposed stringent environmental flow restrictions on the power generation of diversion canal power plants.

At the level of individual countries, China has the highest existing hydropower production (~1.23 PWh in 2021)⁴; it also has the world's largest unused profitable potential (Table 1). Potential development sites in China are concentrated mainly in the mountainous provinces of Tibet, Sichuan, Yunnan and Guizhou (Fig. 1a). This unused profitable potential hydropower of 2.25 PWh yr⁻¹ could meet 30% of China's current electricity demand of 7.19 PWh yr⁻¹. Myanmar, Russia, India and Pakistan also have unused profitable potential in the range 210–340 TWh yr⁻¹ (Fig. 1a and Table 1). In addition, among the top 20 countries with unused profitable hydropower potential, Myanmar, Pakistan, Peru, Nepal, the Democratic Republic of the Congo, Ethiopia and Laos could fully meet their total current electricity demand by developing their unused profitable hydropower resources (Table 1). Meanwhile, Africa's current hydropower generation is 0.14 PWh yr⁻¹, much less than its unused profitable potential (that is, 0.60 PWh yr⁻¹), indicating that hydropower development on the continent is still in its infancy. Most African countries could potentially fully meet their current electricity demand if they were to develop their unused profitable potential (Fig. 2), which would significantly improve Africa's infrastructure and energy situation. Currently, only Mozambique, Zambia, Ethiopia, Egypt and the Democratic Republic of the Congo rank in the top 50 worldwide in hydropower generation, ranging from about 11 to 14 TWh yr⁻¹.

Uprating existing non-powered dams could also increase electricity generation¹⁷. We estimate that the profitable hydropower potential of refurbishing non-powered dams is only 0.23 (0.07, 0.62) (The numbers in parentheses represent 95% confidence intervals) PWh yr⁻¹ (Supplementary Fig. 8 and Methods). This value is an underestimate as it is based on only 29,775 non-powered dams in the global river network (Supplementary Fig. 9). However, the true value may not be substantially higher than our crude estimate because these types of dams tend to be located on river sections where mean discharge is relatively low. Most (92%) of the multiyear mean discharge value of the rivers on which the non-powered dams are located is below 50 m³ s⁻¹, which is lower than the 100–1,200 m³ s⁻¹ range associated with most of our hydropower systems in the virtual network that produce the estimated undeveloped profitable potential (Supplementary Fig. 6). Hydropower development via impoundment structures in locations with relatively low discharge is often not cost-effective from the

perspective of LCOE. Nevertheless, the uncertainty associated with this particular contribution to hydropower potential is an area that requires future work.

One of the greatest challenges for decarbonization is addressing the difficulty in maintaining power grid stability given the imbalance between fluctuating power demand and real-time electricity production by renewable sources³⁰. Pumped hydro energy storage is a tested technology with great potential for worldwide development³¹. Potential river power plant sites with large reservoirs may in some cases be suitable for pumped storage plants. Compared with the global atlas of closed-loop pumped hydro energy storage³², we found that there are 1,214 river power plants globally that overlap with pumped hydropower resources (Supplementary Fig. 10). Future hydropower plants could be potentially situated strategically to leverage this capacity to both generate and store energy efficiently³³.

Whilst we set many constraints on the quantitative framework to minimize the environmental and social displacements associated with hydropower development, developing unused profitable hydropower sites will likely lead to some type of impact. For example, hydropower development fundamentally changes the natural discharge of rivers, disturbs freshwater ecosystems and may contribute to local species extinctions⁷. To address this issue, we disallowed development in many sensitive areas and required that environmental flows be maintained to preserve ecosystem functioning in rivers (see Supplementary Table 3 for a comparison of flow scenarios). Globally, the criteria to maintain critical stream discharges impact profitable hydropower potential (Supplementary Text 2 and Supplementary Fig. 11). If no environmental flow criteria were used, the global profitable potential could be as high as 10.48 PWh yr⁻¹ because maximal volumes of water could be stored and/or diverted to produce hydroelectricity. In contrast, maintaining 90% of the multiyear average river discharge at each hydropower site would decrease the potential to 1.94 PWh yr⁻¹. In comparison, our conservative criterion of 30th percentile of all daily flows in the 38-year dataset leads to the estimate of 5.27 PWh yr⁻¹ profitable potential. Other commonly used flow criteria, such as the Tennant and Tessmann methods¹⁵, produce slightly higher estimates: 6.26 and 5.58 PWh yr⁻¹, respectively (Supplementary Text 2 and Supplementary Fig. 11). Maintaining critical flow is essential in regions such as Southeast Asia, where many globally important biodiversity hotspots exist (Supplementary Fig. 12). Thus, we anticipate that large trade-offs will be needed to support both environmental conservation and hydropower development throughout the region. It will also affect the hydropower potential assessment. This situation is now quite controversial in the Mekong River Basin³⁴.

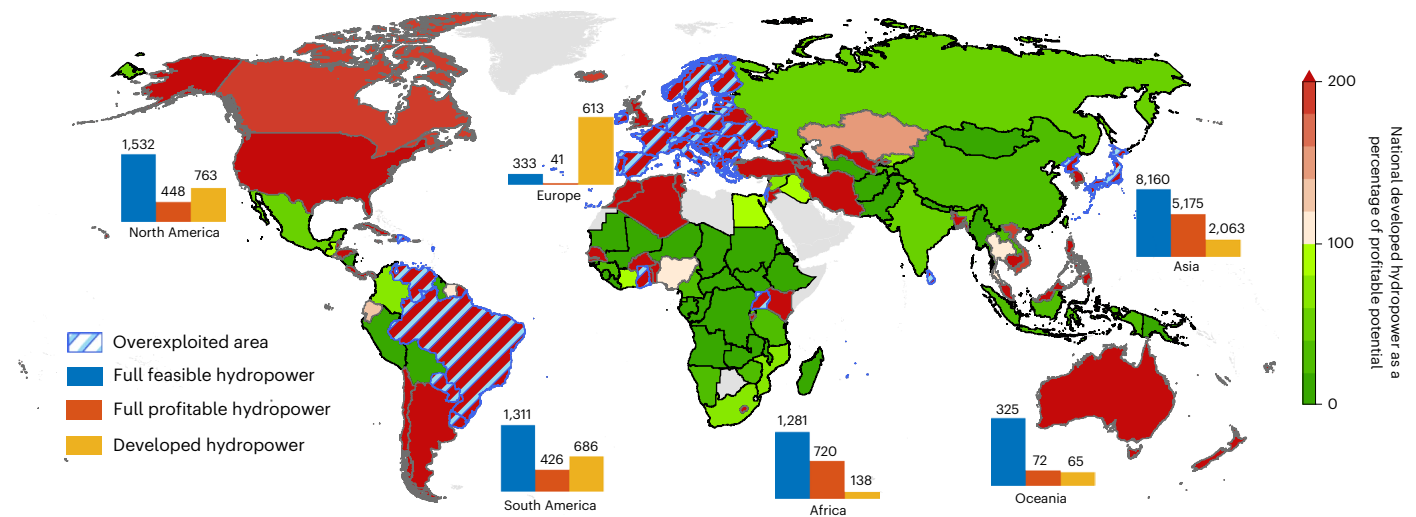


Fig. 3 | Extent of hydropower development for each country and continent.

National developed hydropower as a percentage of full profitable potential. The green areas represent countries in which hydropower development can be continued, the red areas represent countries whose developed hydropower

exceeds the full profitable potential and the red hatched areas indicate countries whose developed hydropower exceeds the full feasible potential. The bar charts represent the full feasible, full profitable and developed hydropower (in TWh yr⁻¹) of each continent.

We also found that the aboveground biomass loss associated with developing the global unused profitable hydropower system sites is 0.143 Pg carbon (PgC), mainly distributed in Asia (0.060 PgC) and North America (0.032 PgC). Globally, the carbon emission intensity of these hydropower system sites is only 0.68 g kWh⁻¹, which is much lower than the carbon emission intensity of coal thermal power plants of 180 g kWh⁻¹ (ref. 35). We estimate that the development of all unused profitable hydropower sites would produce renewable energy with an associated carbon loss equivalent to 3.4 billion metric tonnes of CO₂ emissions per year, or about 8.2% of the current annual anthropogenic CO₂ emissions³⁶. Regionally, the largest inundated aboveground biomass is in Russia (27 TgC), followed by Canada (26 TgC), Myanmar (12 TgC) and China (11 TgC). China has a high number of unused profitable hydropower system sites that would inundate few forests and wetlands because the sites are located in the steep terrain of the Himalayas, where hydropower generation is highly efficient. Moreover, the carbon emission intensity in China is only 0.13 g kWh⁻¹ (Supplementary Fig. 13). We found that Brazil has the highest inundated aboveground biomass loss per kilowatt hour associated with developing its unused profitable potential (7.3 g kWh⁻¹), despite our approach being designed to avoid tropical forests.

Concerning societal impacts, we further estimate that the total displacement of people associated with the development of global unused profitable hydropower system sites is approximately 650,000 people, less than the 1.3 million displaced when China's Three Gorges Dam was constructed³⁷. Our approach excluded locations where inundation would displace more than 50,000 people. This reasonable site selection strategy in our analysis effectively reduces human displacement. To test the sensitivity of the hydropower potential to the magnitude of the displacement threshold, we varied the reservoir displacement threshold from 0 to 50,000 people and re-quantified the global unused profitable potential. When no displacement was allowed, we found that the unused profitable potential was only 2.26 PWh yr⁻¹. However, when the displacement threshold reached 100 people, there was almost no impact on the unused profitable potential (Supplementary Fig. 14). Thus, a much more conservative displacement threshold can be applied, but caution is needed in applying any criteria of this nature because rural and transient populations may not all be accurately represented in published demographic databases. Further, the loss of productive lands needs to be fully factored into compensations. In our assessment, we stipulated that the compensation for

displacement would have a value equivalent to five times the local per capita gross domestic product (GDP), and we compensated for the loss of agricultural lands, forests and grasslands. Compensation increases the cost of energy production, affecting which sites are deemed profitable or feasible.

Our estimate of the global unused profitable potential excludes areas with existing reservoirs. A full potential scenario was produced by removing this constraint and re-quantifying the hydropower potential of each country (Supplementary Fig. 2). By comparing the full feasible (profitable) hydropower potential with developed hydropower data from the International Energy Agency's generation dataset⁴, we were able to assess the level of national hydropower development of each country. Specifically, if a country's hydropower generation exceeds its full feasible potential, we define it as overexploited development. Globally, the world's hydropower generation in 2018 was 4.32 PWh, less than our estimate of the world's full profitable potential (6.87 PWh yr⁻¹). However, the level of global hydropower development shows substantial regional imbalance (Fig. 3).

The developed hydropower in Europe (0.61 PWh yr⁻¹) strongly exceeds its full profitable potential (0.04 PWh yr⁻¹). Considering that Europe has 1.2 million instream barriers³⁸, efforts are currently being made to remove many dams to restore river ecosystems³⁹. The developed hydropower in North America (0.76 PWh yr⁻¹) is also higher than our estimated full profitable potential (0.45 PWh yr⁻¹). However, there is still a fair amount of unused hydropower potential in the Rocky Mountains (Fig. 1). Hydropower development in the United States is almost complete; it has been declining⁴⁰, and its unused profitable potential is equivalent to only 2% of the current electricity demand (Table 1). In Canada, some peatland has already been inundated by reservoirs, enhancing hydropower generation while degrading ecosystems that are important carbon stores. Hydropower currently contributes 59% of Canada's electricity demand⁴¹, and future hydropower development could continue in the Rocky Mountains (Fig. 1a and Table 1). Giant reservoirs in South America have already been built in tropical forests⁴², leading to the overexploitation of hydropower in Brazil, Paraguay and Uruguay. The unused profitable potentials in these countries meet only 3% of their current electricity demands. Peru, Bolivia and Colombia in the Andes have yet to exceed their full profitable potential.

Many countries in Asia and Africa also have not maximized their profitable hydropower potentials. Specifically, the Himalayas,

Asia's water tower, have the greatest potential for hydropower expansion, and many planned reservoirs are already under construction in the region⁴³. As this region includes the world's largest transboundary river basin (Brahmaputra), China, India, Bhutan and Bangladesh need to strengthen cooperation in hydropower development and river flow management⁴⁴. Such strong cooperation is needed for all international rivers worldwide to avoid conflicts. In addition, with climate change accelerating the melting of glaciers⁴⁵, there is likely to be a need to build more reservoirs to withstand flooding and maintain year-round water supply^{46,47}, but this approach must be balanced with the risks of outburst floods occurring on dammed rivers. Additionally, much of the world's population growth may occur in Africa, where hydropower development has not been substantial so far. Given the need to improve on all types of security (for example, food, water, energy and livelihood), hydropower systems that can be developed in multifunctional reservoirs could be prioritized if they can be developed sustainably⁵. With regard to efficient and sustainable energy production, multifunctionality could involve combining traditional hydropower generation, pumped storage and floating photovoltaic systems.

Our approach of using a consistent and transparent framework to analyse hydropower development potential indicates that the global unused profitable hydropower potential is 5.27 PWh yr⁻¹, which is 60% higher than the recent estimate made by Gernaat et al.¹². Through reasonable hydropower development, the global hydropower capacity could double to 9 PWh yr⁻¹, implying that hydropower could play a larger role in the future energy resource structure⁴⁸. Most of these undeveloped hydropower system sites are located in the highlands of Asia, particularly in China, with substantial potential remaining in Africa and other locations with high mountain chains. With many countries in developing regions expected to experience substantial population and infrastructure growth in the future, hydropower development could potentially play a key role in their overall development goals. Complicating the issue of harnessing this unused profitable hydropower potential is the management of river flow to preserve the environment, people's livelihoods and geopolitical stability. Our quantitative framework for assessing hydropower potential offers a guide to decision-making towards achieving the SDGs. As such, hydropower development worldwide could proceed with fewer negative environmental and social impacts than in the past.

Methods

Discharge dataset

Our estimate of hydropower potential using the 38-year (1979–2016) global discharge dataset from the Terrestrial Hydrology Research Group at Princeton University²¹ contains discharge information on 2.89 million rivers globally. This dataset vectorizes the global river network using the latest global high-resolution MERIT DEM^{49,50} (3" resolution), producing modelled river routes consistent with satellite-based information. The product provides 0.05° daily river discharge records for 2.89 million global rivers over 38 years (1979–2016). The records were produced using the Variable Infiltration Capacity land surface model and the Routing Application for Parallel computation of Discharge river routing model. Precipitation forcing data were obtained from a 0.1° global product that merged gauge-, reanalysis- and satellite-based data⁵¹. Run-off simulations were constrained using a set of machine learning-derived, global run-off characteristics maps for grid-by-grid model calibration and bias correction. Daily and monthly observations from more than 14,000 hydrological stations were used for validation. More than half (59%) of the stations' relative errors in multiyear mean discharge are within 20%, and 80% of the relative errors are within 40% (Supplementary Fig. 1). To be consistent with the discharge dataset, we used MERIT Basins²¹ and hydrologically adjusted elevations from MERIT Hydro as the river network dataset and digital elevation model (DEM) dataset⁵⁰ from which other geographical information was derived relating to hydropower plant construction (for example,

dam location/width, diversion canal/tunnel placement and inundation area) and impact.

Reservoir datasets

To generate a new reservoir dataset that includes the data of as many installed hydropower plants in the world as possible, we first extracted the latest global reservoir database from OpenStreetMap²², which includes 50,591 dams and 425,455 reservoirs globally. Next, we integrated the database with the previous three global reservoir datasets: GRanD²³, GOODD²⁴ and GeoDAR²⁵. GRanD provides spatial information on 7,250 global reservoirs, GOODD gives 38,667 dam locations globally, and GeoDAR provides 23,680 dam locations and spatial information on 20,214 reservoirs globally. As the locations of dams are represented only as points in these databases, we set a 5 km buffer zone for each dam.

Hydropower potential calculations

The theoretical hydropower potential E_T (kW) was calculated as follows:

$$E_T = 9.81HQ \quad (1)$$

where H is the hydraulic head (m) of the river and Q is the discharge (m³ s⁻¹).

Using equation (2), we calculated the annual theoretical hydropower potential (kWh) from the mean daily discharge $\bar{Q}$ and H , derived as an altitudinal gradient determined from the DEM:

$$E_T = 9.81H\bar{Q} \times 24 \times 365 \quad (2)$$

As a baseline, we first calculated the theoretical hydropower potential for each country. As a large portion of the energy of a natural river is dissipated by friction, we need to build hydropower plants to reduce hydraulic head loss. Due to high hydropower plant costs, our assessment distinguishes feasible and profitable potential (definitions are provided in Supplementary Table 1 and Supplementary Fig. 2). We modelled the establishment of virtual hydropower system sites at an interval of 4.5 km for 2.89 million rivers worldwide (a total of 4.14 million sites) and quantified the feasible and profitable potential of hydropower at each site.

We considered the same two main hydropower systems¹²: river power plants and diversion canal power plants, each of which can have different environmental impacts. River power plants have associated inundation areas that may cause damage to nature reserves, forests and farmland, and they may disrupt the livelihoods of local populations. Diversion canal power plants do not inundate areas, but they change the natural structure/form of a river, disconnecting natural flow paths.

We define environmental flow as the 30th percentile of daily discharge in the last 38 years. We analysed rivers with a multiyear average discharge of less than 1,000 m³ s⁻¹ and allocated half of the discharge greater than the environmental flow for electricity generation by diversion canal power plants. We calculated the feasible and profitable hydropower potential E_E (kWh) from the following equation:

$$E_E = \sum 9.81 \times \min(Q_t, Q_D) H_D \eta / N \quad (3)$$

where Q_t is the discharge rate reducing environment flow. For river power plants, Q_t is calculated as:

$$Q_t = \max(Q - Q_{\text{eflow}}, 0) \quad (4)$$

For diversion canal power plants:

$$Q_t = 0.5 \times \max(Q - Q_{\text{eflow}}, 0) \quad (5)$$

In equations (4) and (5), Q is the discharge of the river and Q_{eflow} is the 30th percentile of daily discharge during the 38-year period,

which is a relatively conservative estimate of profitable potential (Supplementary Text 2 and Supplementary Fig. 15). To make full use of the hydropower, Q_b in equation (3) incorporates the 97th percentile of Q_t recorded during the 38-year period. $N = 38$ (year). The term η is the efficiency of river power plants (0.7) or the diversion canal power plants (0.9)¹². For river power plants, H_b is the dam height, and for the diversion canal power plants, H_b is calculated as:

$$H_b = H_G - h_f \quad (6)$$

where H_G is the altitudinal gradient between the water inlet and the generator and h_f represents the frictional head loss. h_f is calculated using the Darcy–Weisbach formula:

$$h_f = \lambda \frac{l}{d} \frac{v^2}{2g} \quad (7)$$

where l is the pipe length (m), d is the pipe diameter, g is the gravitational acceleration and v is the water velocity in the pipe. We used the Blasius equation to calculate λ from the Reynolds number Re :

$$\lambda = 0.316 Re^{-0.25} \quad (8)$$

Constraints on hydropower system simulation

Constraints on river power plants. The dam height is the most critical parameter of river power plants as it is fundamental to the determination of energy production, dam cost, compensation for flooded farmland, population displacement and various other environmental impacts. We parameterized the dam height from 10 to 300 m in the construction of dams at virtual sites¹². Dams were built virtually in two directions, east–west and north–south, to calculate how wide the dam would need to be to block the valley completely. We chose the smaller width of the dam in the two directions as the construction direction. If the width of a dam was greater than 3,000 m in both directions, this dam height of the virtual site was discarded.

To determine the direction of inundation after constructing the dam at the virtual site, we identified the upstream and downstream segments of the river using the DEM and simulated the inundation area by setting the virtual hydropower plant location as the starting inundation point. Points with DEM values lower than the virtual site's DEM value plus the dam height were selected gradually upstream along the inundation direction. Each new inundation point had to be connected with existing inundation points to ensure the continuity of the inundation area. The search continued until no point's DEM value was lower than the virtual site's DEM plus dam height. In this way, we could determine the inundation area¹². However, if the inundation area already had a reservoir (based on the reservoir datasets) or the environmental impact was deemed too negative (based on the constraints below), dam construction at that location was removed from the model. Further, to reduce the impact of reservoir displacement, the population of the inundation area had to be less than 50,000 people, otherwise the site was excluded. While ensuring water reliability, the reservoir's volume should be less than the two-year total discharge of the river. Meanwhile, we considered the forest, farmland, grassland and migrant population in the inundation area to calculate dam inundation compensation payments. Specific compensation calculations are shown in Supplementary Table 4.

To minimize environmental harm, we used several environmental-based constraints to exclude development in (1) protected areas (WDPA categories I and II, Strict Nature Reserves, Wilderness Areas and National Parks)⁵², (2) UNESCO (United Nations Educational, Scientific and Cultural Organization) World Heritage Sites⁵³, (3) large lakes (Global Lakes and Wetlands Database, Level 1; ref. 54), (4) high-value (biodiversity and carbon) tropical rainforests⁵⁵ and peatlands⁵⁶, and

(5) locations where inundation would displace more than 50,000 people⁵⁷. We also considered various economic constraints associated with construction in areas with complex geology and seismic hazards. For the former, we used the Harmonized World Soil Database⁵⁸ to identify locations with 'soft' rocks that would necessitate higher construction costs to build deeper foundations. To assess the risk of earthquakes, we used the GSHAP Global Seismic Hazard Map⁵⁹, which depicts the seismic hazard as peak ground acceleration (PGA) with a 10% probability of exceedance in 50 years, corresponding to a return period of 475 years. Locations with a PGA greater than 0.7 m s^{-2} require more cost to improve the seismic resistance.

Constraints on diversion canal power plants. The most critical parameters for diversion canal power plants are the water intake position, which determines the energy production, and the length and diameter of the pipe. To reduce the impact of diversion canal power plants on a river network's natural topology, upstream water intake and the virtual site have to be connected in a natural river network to ensure that the diversion hydropower station only affects the inlet and outlet section of the river flow. Meanwhile, we only analysed rivers with a multiyear average discharge of less than $1,000 \text{ m}^3 \text{ s}^{-1}$ and allocated half of the available discharge that is greater than the environmental flow for electricity generation. Further, the affected streamline and pipe were constrained to not pass through farmland or cities due to excessive costs arising from disturbance to the supply of agricultural or domestic water demand. The natural river network within 25 km upstream of the virtual hydropower station site was searched to identify a potential water intake point. We used the Dijkstra⁶⁰ algorithm to identify the connectivity of the water intake point and the virtual hydropower station site, ensuring connectivity along the river valley.

Costs of the hydropower system

In deriving the feasible potential, we used the lowest LCOE as the evaluation criterion. We based the cost of a hydropower development system on the data from refs. 12,61. We classified the costs as turbine, power station, electrotechnical equipment, fish passage, miscellaneous, power-line connection, dam, land loss costs, population displacement compensation, headrace tunnel and penstock piping. We also factored in two types of compensation rate: (1) five times the local per capita GDP for displaced people⁶² and (2) US\$475, US\$10,134 and US\$3,460 per hectare where virtual reservoirs inundate forests, farmland and grasslands, respectively^{63,64}. The global power-line network from OpenStreetMap³⁷ was used to determine connectance distances from the hydropower system to the power grid using high-voltage power lines. The LCOE has an associated 10% investment rate and a 40-year lifetime. The geometric parameters for the two hydropower systems were determined by terrain analysis (based on the constraints of hydropower system simulations). The equations for all components considered are shown in Supplementary Table 4, and construction cost sensitivity analyses are shown in Supplementary Text 3 and Supplementary Fig. 15.

We calculated the LCOE of different dam heights at each virtual hydropower station site and selected the dam height with the lowest LCOE. We compared the LCOE of different water intakes and selected the lowest LCOE as the virtual hydropower station's optimal water intake. If the LCOE was less than US\$0.5 kWh^{-1} , the hydropower system was considered to have feasible potential. If the LCOE was less than US\$0.1 kWh^{-1} , the hydropower system was considered to have profitable potential¹².

Due to the high-density sampling of the river network, the hydropower systems at different virtual sites could potentially overlap spatially. To avoid this problem, the LCOE of each hydropower system was ranked from lowest to highest, then sequentially we added virtual hydropower plants into an empty global map starting with the lowest LCOE plant. If the area of the hydropower system to be placed on the map at each step did not overlap with the area of existing hydropower

systems on the map, the hydropower system was retained. This procedure was repeated until the LCOE of the next hydropower system was considered higher than US\$0.5 kWh⁻¹.

Impact analysis

To understand the potential environmental impacts of unused profitable hydropower system sites, we examined the overlap of reservoir inundation areas with aboveground biomass and the ranges of endangered species. The former information was obtained from *Global Aboveground and Belowground Biomass Carbon Density Maps for the Year 2010*⁶⁵. We calculated the aboveground biomass of the inundated areas of profitable hydropower systems sites and the intensity of aboveground biomass per kilowatt hour (Bioenergy) was calculated by dividing the inundated aboveground biomass (B) by the 40-year electricity generation of the profitable hydropower plants (E):

$$\text{Bioenergy} = \frac{B}{40 \times E} \quad (9)$$

Information on endangered species was obtained from the Global Amphibian and Mammal Species Richness Grids of the International Union for Conservation of Nature⁶⁶. We set the endangered species score for each hydropower system to 100. According to the endangered species dataset, ten points are deducted for each endangered species in the hydropower plant area; a minimum score of zero indicates the presence of at least ten endangered species. Then we calculated the endangered species score (S) of the country according to the formula:

$$S = \frac{\sum_{i=1}^k (E \times S_{\text{danger}})}{\sum_{i=1}^k E} \quad (10)$$

where E is the annual electricity generation of the profitable hydropower system and S_{danger} is the endangered species score of the profitable hydropower system site.

We identified biodiversity hotspots using two species pools: all species belonging to any International Union for Conservation of Nature (IUCN) Red List category and threatened species listed as CR (critically endangered), EN (endangered) and VU (vulnerable) on the IUCN Red List (available at <https://www.iucnredlist.org/resources/other-spatial-downloads>). We define biodiversity hotspots as the upper 2.5% of grid cells with the highest range-size rarity or species richness value. We judged whether the hydropower system is located in biodiversity hotspots, and then we calculated what percentage of a country's profitable potential is built in biodiversity hotspots according to the formula:

$$S_{\text{hotspot}} = \frac{\sum_{i=1}^k E_{\text{hotspot}}}{\sum_{i=1}^k E} \times 100\% \quad (11)$$

where S_{hotspot} is the ratio of hydropower potential in biodiversity hotspots to national profitable potential, E is the annual electricity generation of the profitable hydropower system and E_{hotspot} is the annual electricity generation of the profitable hydropower system built in biodiversity hotspots.

To quantify the impact of social displacement caused by reservoir development, we set the reservoir migration threshold from 0 to 50,000 people and simulated the global unused profitable potential at each migration threshold.

Assessment of energy potential at non-powered dams

To assess the global profitable hydropower potential of non-powered dams, we extracted the latest global reservoir databases

from OpenStreetMap²² (50,591 dams) and GOODD²⁴ (38,667 dams). We excluded overlapping dams in the two dam databases and spatially matched the dams to the global river network dataset. Some dams with missing river network information are likely to be located in small streams (considering the 25 km² channelization threshold of our river network) and thus have low potential for producing electricity. Through quality control and spatial matching, we found 29,775 non-powered dams in the global river network (Supplementary Fig. 9).

Due to the lack of dam height data in OpenStreetMap and GOODD, we chose dam height data from the US National Inventory of Dams (NID) and excluded the dams that can generate electricity. There are 81,562 dam heights in the NID, of which 76,419 are less than 15 m. We assumed that the dam height distribution of global non-powered dams is the same as that of non-powered dams in the United States and used the Monte Carlo method to simulate the dam height of global non-powered dams. Nevertheless, the uncertainty associated with this contribution to hydropower potential is an area that needs future work. If a more complete global reservoir dataset that includes dam heights becomes available in the future, the profitable hydropower potential assessment of non-powered dams will be more accurate.

Data availability

The discharge dataset is available at <http://hydrology.princeton.edu/data/mpan/GRFR/discharge/daily/>, the river network dataset is available at http://hydrology.princeton.edu/data/mpan/MERIT_Basins/MERIT_Hydro_v07_Basins_v01/, the DEM dataset is available at http://hydro.iis.u-tokyo.ac.jp/~yamada/MERIT_Hydro/, the GRanD database is available at <https://www.globaldamwatch.org/grand>, the Global Georeferenced Database of Dams (GOODD) dataset is available at <https://www.globaldamwatch.org/goodd>, Georeferenced global dam and reservoir (GeoDAR) data are available at <https://zenodo.org/record/6163413>, the latest global reservoir and power-line datasets can be extracted from <https://www.openstreetmap.org/>, the WDPA database is available at <https://www.protectedplanet.net/en>, the natural and mixed World Heritage Sites are available at <https://www.arcgis.com/home/item.html?id=ef1ecce8fa3e41d89688be6199b5b32c>, large lakes are available at <https://www.worldwildlife.org/pages/global-lakes-and-wetlands-database>, the tropical rainforests dataset is available at <https://glad.umd.edu/dataset/primary-forest-humid-tropics>, the peatlands dataset is available at <https://archive.researchdata.leeds.ac.uk/251/>, the population dataset is available at <https://landscan.ornl.gov/>, the electricity consumption dataset is available at <https://www.iea.org/data-and-statistics/data-browser/?country=WORLD&fuel=Energy%20consumption&indicator=TotElecCons>, the electricity supply dataset is available at <https://www.iea.org/data-and-statistics/data-browser/?country=WORLD&fuel=Energy%20supply&indicator=ElecGenByFuel>, the global aboveground biomass carbon density maps are available at https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1763, the IUCN Red List data are available at <https://www.iucnredlist.org/resources/other-spatial-downloads>, the Global Amphibian and Mammal Species Richness Grids of the ICUN are available at <https://sedac.ciesin.columbia.edu/data/set/species-global-amphibian-richness-2015> and <https://sedac.ciesin.columbia.edu/data/set/species-global-mammal-richness-2015>, the GDP dataset is available at <https://datadryad.org/stash/dataset/doi:10.5061/dryad.dk1j0>, the Global Seismic Hazard Map is available at <http://gmo.gfz-potsdam.de/>, global land cover data are available at <http://www.esa-landcover-cci.org/?q=node/197> and the global soil dataset is available at <http://www.fao.org/soils-portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/>. All datasets are also available from the corresponding author upon request.

Code availability

The scripts used to generate all the results are MATLAB (R2018b). All data and code are available at <https://github.com/xurr2020/GlobalHydropower>.

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Author contributions

Conceptualization: R.X. and Z.Z. Methodology: R.X., Z.Z., A.D.Z., L.E.B., J.H. and D.V.S. Investigation: R.X. Visualization: R.X. Funding acquisition: Z.Z., L.E.B. and J.H. Project administration: Z.Z. Supervision: Z.Z. Writing—original draft: R.X. Writing—review and editing: all authors contributed to interpreting results, and writing and editing the manuscript.

Competing interests

The authors declare no competing interests.

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