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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. Here, we perform 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 find 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, developed 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 fuels[1]. 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 electricity[4]. Looking ahead, hydropower is expected to play a key role in the 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 implications[5], including the disruption of river ecosystem structure and functioning, 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 sustainable development goals in the 21st century (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.

Prior quantitative studies have estimated that the global theoretical hydropower potential ranges from 30.67 to 127.58 PWh per year[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: (i) low spatiotemporal resolution in hydrological models; (ii) utilization of coarse river network maps that cannot accurately represent river planform geometry and associated environmental conditions; (iii) lack of verification against sufficient river discharge gauge observations, and (iv) 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, prior estimates have rarely incorporated restrictions that limit many negative impacts of hydropower plant construction[14]. For example, the most up-to-date estimates made by Gernaat *et al.*[12] only 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 infrastructure[15]. Also important is the consideration of non-hydropower dams that can be converted to generate hydroelectricity, as well as upgrading existing hydropower dams to maximize full potential[16,17]. These relatively quick modifications would reduce environmental issues compared with developing new plants. However, since hydropower generation requires high water flow and hydraulic head, it is unclear whether refurbishing non-powered dams is either economically or practically possible.

Within the vision to develop the global unused hydropower potential sustainably[18-20], we perform 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 the environmental and social impact. The analysis is based on reconstructing global naturalized river flows on 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 is comprehensively evaluated against the daily and monthly flow records of over 14,000 hydrological stations (Fig. S1). For this virtual network, we consider the same two main hydropower systems[12], 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 of these two general types of systems. We use the latest global high-resolution MERIT DEM (3 arc-second resolution) and calculations of the Levelized Cost of Energy (LCOE; Fig. S2, see Methods) to determine the optimal type and size of hydropower systems at each potential site in the network.

To avoid sensitive locations, we apply strict criteria to limit environmental and social impacts. For example, we directly exclude 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 new reservoir dataset that includes data for all installed hydropower plants worldwide, we integrate global reservoir datasets (e.g., OpenStreetMap[22], GRanD[23], GOODD[24], and GeoDAR[25]) and include a total of 445,669 reservoirs in our assessment (see Methods). Importantly, we stipulate that a new hydropower station must maintain an environmental flow that will support downstream river ecosystem integrity and water availability during baseflow conditions, particularly within dry seasons. In cases where sites identified for hydropower expansion are too closely situated, we retain the one with the lowest LCOE (Fig. S2). Collectively, this approaches us to estimate the unused feasible and profitable hydropower potential to be developed worldwide (definitions in Table S1, Fig. S2). Finally, we identify 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} (Fig. S3; Text. S1), slightly higher than the two most recent estimates of 50-52 PWh yr^{-1} [ref.12,13]. We estimated the global unused feasible and profitable hydropower potential is 10.89 PWh yr^{-1} and 5.27 PWh yr^{-1}, respectively. The global profitable hydropower potential has an upward trend, with an annual increase of 0.008 PWh yr^{-1} from 1979 to 2016 (Fig. S4). However, the spatial distribution of global hydropower profitable potential trends is different. The profitable potential in Canada, Russia, Andes, southern Africa, Indonesia, and Papua New Guinea has increased over the past 40 years, while profitable potential in the western United States, Europe and Central Africa has decreased (Fig. S5). Furthermore, future climate change can 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 is extremely challenging to be quantified[26,27]. Regional power grid interconnection can mitigate climate impacts on hydropower[28]. Thus, future studies and hydropower policy development also need to address climate change impacts on a case-by-case basis.

In our analysis, impoundment power plants account for 81% of the global unused profitable potential, compared with 19% for diversion hydropower plants. The multi-year mean discharge at most impoundment power plants ranges between 100 and 1,200 $m^3 s^{-1}$, compared with 10 to 150 $m^3 s^{-1}$ for diversion plants (Fig. S6). Most of these hydropower systems identified in our analysis have installed capacities between 100 MW and 650 MW, but some have capacities less than 50 MW (Fig. S7). Few small plants are identified in our approach because they were either not cost-effective (high LCOE), could not be designed to ensure sufficient environmental flows could be maintained, or they would have encroached on sensitive areas, particularly forests. The small diversion hydropower plants in the Himalayas and the Andes are appropriate to include tributary streams that steep relief allows sufficient fall heights to generate electricity efficiently. Contrary to ongoing development (e.g., in Vietnam), our analysis does not support small diversion plant development on tiny headwater streams because of their impact on the environment and economic costs. Our analysis 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 to 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 modeling. Notably, Asia's unused profitable potential (3.90 PWh yr^{-1}) is three times greater than the prior estimate[10]. While the spatial distribution of unused profitable hydropower sites in high-mountain Asia is roughly consistent with the prior assessment, the energy production cost is much lower in the high-relief Himalaya than in other parts of the world (Fig. 1c), leading to our finding of a greater profitable potential than 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, Nepal of Asia, and D.R. Congo, Ethiopia, and Zambia in Africa (Table 1, Table S2). North America and South America, which have similar cost supply curves, and their unused profitable potential is 0.33 PWh yr^{-1} 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 greatly[29]. Therefore, our estimate for South America's unused profitable potential is less than half of that by Gernaat *et al.* [12], which did not considered the conservation of tropical forests. Oceania and Europe have limited unused profitable potential (Fig. 1c). We further find that Europe's unused profitable potential is only one-seventh that of Gernaat *et al.*[12], largely because we impose 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]; also has the world's largest unused profitable potential (Table 1). Potential development sites are concentrated mainly in the mountaious 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 potentials in the 210-340 TWh yr^{-1} (Fig. 1a; Table 1). In addition, among the top 20 countries with unused profitable hydropower potential, Myanmar, Pakistan, Peru, Nepal, D.R. Congo, Ethiopia, and Laos could fully meet their total current electricity demand by developing the 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 (*i.e.*, 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 can significantly improve Africa's infrastructure and energy situation. Currently, only Mozambique, Zambia, Ethiopia, Egypt, and DR Congo rank in the top 50 worldwide in hydropower generation, ranging from about 11 to 14 TWh yr^{-1}.

Uprating existing non-powered dams can also increase electricity generation[17]. We estimate that the profitable hydropower potential of refurbishing non-powered dams is only 0.23 [0.07, 0.62] PWh yr^{-1} (Fig. S8; see Methods). This estimate is underestimated as it is based on only 29,775 non-powered dams in the global river network (Fig. S9). 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 multi-year mean discharge value of the rivers where the non-powered dams are located is below 50 m^3 s^{-1}, which is lower than the 100 and 1,200 m^3 s^{-1} range associated with most of our hydropower systems in the virtual network that produce the estimated undeveloped profitable potential (Fig. S6). 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 of needed future work.

One of the greatest challenges for decarbonization is addressing the difficulty in maintaining power grid stability given the unbalance between fluctuating power demand and real-time electricity production by renewable sources[30]. Pumped hydro energy storage (PHS) is a tested technology with great potential for worldwide development[31]. Potential river power plants sites with large reservoirs may in some cases, be suitable for pumped storage plants. According to the global atlas of closed-loop pumped hydro energy storage[32], we find that there are 1,214 river power plants globally that overlap with pumped hydropower resources (Fig. S10). The future hydropower plants can be potentially situated strategically to leverage this capacity to both generate and store energy efficiently[33].

Whilst our quantitative framework set many constraints to minimize the environmental and social displacements associated with hydropower development, developing the unused profitable hydropower system 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 extinctions[7]. To address this issue, we disallow development in many sensitive areas and require that environmental flows be maintained to preserve ecosystem functioning in rivers (see Table S3 for a comparison of flow scenarios). Globally, the criteria to maintain critical stream discharges significantly impact profitable hydropower potential (Text S2, Fig. S11). If no environmental flow criteria are used, global profitable potential could be as high as 10.48 PWh yr^{-1} because maximal volumes of water are stored and/or diverted to produce hydroelectricity. In contrast, maintaining 90% of the multi-year average river discharge at each hydropower site would decrease the potential to 1.94 PWh yr^{-1}. In comparison, our conservative criteria of Q30 (30th percentile of all daily flows in the 38-year dataset) lead to the estimate of 5.27 PWh yr^{-1} profitable potential. Other commonly used flow criteria, such as the Tennant and Tessmann methods[13] produce slightly higher estimates: 6.26 PWh yr^{-1} and 5.58 PWh yr^{-1}, respectively (Text S2; Fig. S11). Maintaining critical flows is essential in regions such as Southeast Asia, where many globally-important biodiversity hotspots exist (Fig. S12). Thus, we anticipate that large tradeoffs 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 on within the Mekong River Basin[34].

We also find that the aboveground biomass losses associated with developing the global unused profitable hydropower system sites to be 0.143 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 estimated that the development of all unused profitable hydropower sites would produce renewable energy with an associated carbon loss equivalent to 3.4 billion tons of CO_2 emissions per year, or about 8.2% of the current annual anthropogenic carbon dioxide emissions[36]. 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 unused profitable hydropower system sites inundate few forests and wetlands because hydropower generation is highly efficient in the steep terrain of the Himalaya. The carbon emission intensity in China is only 0.13 g kWh^{-1} (Fig. S13). 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 thousand people, less than the 1.3 million displaced when the Three Gorges Dam was constructed[37]. Our approach excludes locations where inundation would displace more than 50,000 people. This reasonable site selection strategy effectively reduced the human displacement in our analysis. To test the sensitivity of the hydropower potential to the magnitude of the displacement threshold, we vary the reservoir displacement threshold from 0 to 50,000 people and re-quantify the global unused profitable potential. When any displacement is not allowed, we find that the unused profitable potential is only 2.26 PWh yr^{-1}. However, when the displacement threshold reaches 100 people, there is almost no impact on the unused profitable potential (Fig. S14). Thus, a much more conservative displacement threshold can be applied, but caution is needed in applying any criteria of this nature because all rural and transient populations may not be accurately represented in published demographic databases. Further, the loss of productive lands needs to be factored fully into the compensations. In our assessment, we stipulated that the compensation for displacement would have a value equivalent to five-fold the local per capita 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. Here, a full potential scenario is produced by removing this constraint and re-quantifying the hydropower potential of each country (Fig. S2). By comparing the full feasible (profitable) hydropower potential with developed hydropower data from the IEA's generation dataset[4], we are able to assess the national hydropower development stage of each country. Specifically, if a country's hydropower generation exceeds its full feasible potential, we define it as an 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 world's hydropower development stage 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 barriers[38], efforts are currently underway to remove many dams to restore river ecosystems[39]. 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 declining[40], and its unused profitable potential is equivalent to only 2% of the current electricity demand (Table 1). In Canada, some reservoirs have already inundated peatland, enhancing hydropower generation meanwhile degrading ecosystems that are important carbon stores. Hydropower currently contributes to 59% of Canada's electricity demand[41], and future hydropower development could continue in the Rocky Mountains (Fig. 1a, Table 1). Giant reservoirs in South America have already been built in tropical forests[42], leading to 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 have also 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 underway in the region[43]. 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 management[44]. Such strong cooperation is needed for all international rivers worldwide to avoid conflicts. In addition, with climate change accelerating the melting of glaciers[45], there is likely to be a need to build more reservoirs to withstand the floods and maintain water supply year-round[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 to date. Given the need to improve on all types of security (food, water, energy, livelihood), hydropower systems that can be developed on multi-functional reservoirs could be prioritized if they can be developed sustainably[5]. With regard to efficient and sustainable energy production, multi-functionality could apply to combining traditional hydropower generation, pumped storage, and floating photovoltaic systems.

Our approach of using a consistent and transparent framework to analyze 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 occupy a larger role in the future energy-resource structure[48]. 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. Many countries in developing regions are anticipated to experience substantial population and infrastructural growth in the future, hydropower development can potentially play a key role in their overall development goals. Complicating the issue of harnessing this unused profitable hydropower potential is managing river flows to preserve the environment, people's livelihoods, and geopolitical stability. Our quantitative framework to assess hydropower potential offers a means to guide decision-making toward achieving Sustainable Development Goals. As such, hydropower development worldwide could proceed with fewer negative environmental and social impacts than in the past.

Methods

1. Discharge dataset

Our estimate of hydropower potential using the 38 years (1979-2016) global runoff dataset from the Terrestrial Hydrology Research Group at Princeton University[17] contains discharge information on 2.89 million rivers globally. It vectorizes the global river network by the latest global high-resolution MERIT DEM[49,50] (3" resolution, or ~90 m at the equator), producing modeled river routes consistent with satellite-based information. The product provides 0.05° daily river discharge records for 2.89 million global rivers for 38 years (1979-2016). The records are produced using the Variable Infiltration Capacity (VIC) land surface model and Routing Application for Parallel computation of Discharge (RAPID) river routing model. Precipitation forcing is from a 0.1° global product that merged gauge-, reanalysis-, and satellite-based data[51]. Runoff simulations are constrained using a set of machine learning-derived, global runoff characteristics map for the grid by grid model calibration and bias correction. Daily and monthly observations from more than 14,000 sites are used for validation. More than half (59%) of the stations' multi-year mean discharge simulation relative errors are within 20%, and 80% of the stations' relative error is within 40% (Fig. S1). To be consistent with the discharge dataset, we use MERIT Basins[21] and Hydrologically Adjusted Elevations from MERIT Hydro as the river network dataset and DEM dataset[50] from which other geographical information is derived regarding hydropower plant construction (e.g., dam location/width; diversion canal/tunnel placement; inundation area) and impact.

2. Reservoir datasets

To generate a new reservoir dataset that includes the data of all installed hydropower plants in the world as much as possible, we first extract the latest global reservoir database from OpenStreetMap[22], including 50,591 dams and 425,455 reservoirs globally. Next, we integrate the database with the previous three global reservoir datasets: GRanD[23], GOODD[24], and GeoDAR[25].

GRanD has spatial information on 7,250 global reservoirs. GOODD has 38,667 dam locations globally. GeoDAR has 23,680 dam locations and 20,214 reservoir spatial information globally. Since the locations of dams are represented only as points in these databases, we set a 5 km buffer zone for each dam.

3. Hydropower potential calculations

Theoretical hydropower potential E_T (kW) is calculated as follows:

$$E_T = 9.81HQ \tag{1}$$

where H is the hydraulic head (m) of the river, Q is the discharge ($\mathrm{m}^3\ \mathrm{s}^{-1}$).

Following Equation 2, we calculate the annual theoretical hydropower potential (kWh) from the mean daily discharge ($\bar{Q}$) and H, which is derived as an altitudinal gradient determined from the DEM.

$$E_T = 9.81H\bar{Q} \times 24 \times 365 \tag{2}$$

As a baseline, we first calculate the theoretical hydropower potential for each country. Since a large portion of the energy of the natural river are dissipated by friction, we need to build hydropower plants to reduce hydraulic head loss. Due to the high hydropower plant cost, our assessment distinguishes feasible and profitable potential (definitions in Table S1, Fig. S2). We model 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 quantify the feasible and profitable potential of hydropower at each site.

We consider the same two main hydropower systems[12]: 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, farmland; and may disrupt local populations' livelihoods. Diversion canal power plants do not inundate areas, but they change the natural structure/form of a river, disconnecting nature flow paths.

We define environmental flow as the 30th-percentile of daily discharge in the last 38 years. We analyze rivers with a multi-year average discharge of lower than 1,000 m^3 s^{-1} and allocate half of the discharge higher than the environmental flow for electricity generation for diversion canal power plants. We calculate feasible and profitable hydropower potential (kWh) from the following equation:

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

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

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

For diversion canal power plants:

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

In Equations 4 and 5, Q is the discharge of the river, and Q_{eflow} is 30th-percentile of daily discharge during the 38-year period, which is a relatively conservative estimate of profitable potential (Text. S2, Fig. S15). To make full use of hydropower, Q_D in Equation 3 incorporates the 97th-percentile of Q_t recorded during the 38-year period. 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_D is the dam height, and for diversion canal power plants, H_D is calculated as:

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

where H_G is the altitudinal gradient between the water inlet and the generator, h_f represents frictional head loss. h_f is calculated by 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 a pipe. We use the Blasius equations to calculate λ from the Reynolds number:

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

4. Constraints on hydropower system simulation

4.1 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 parameterize the dam height from 10 to 300 meters in the construction of dams at virtual sites[12] Dams are virtually built in two directions, east-west and north-south to calculate how wide the dam would need to be to block the valley completely. We choose the smaller width of the dam in the two directions as the construction direction. If the dam's width is greater than 3,000 meters in both directions, this dam height of the virtual site is discarded.

To determine the direction of inundation after constructing the dam at the virtual site, we identify the upstream and downstream segments of the river using the DEM and simulate 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 are selected gradually upstream along the inundation direction. Each new inundated point had to be connected with existing inundation points to ensure the continuity of the inundation area. The search continues until no point's DEM value is lower than the virtual site's DEM plus dam height. In this way, we can determine the inundation area[12]. However, if the inundation area already had a reservoir (based on the reservoir datasets) or the environmental impact is deemed too negative (based on constraints below), dam construction at that location is removed from the model. Further, to reduce the impact of reservoir migration, the inundation area's population is must less than 50,000 people, otherwise the site is excluded. While ensuring water reliability, the reservoir's volume should be less than the two-year total discharge of the river. Meanwhile, we consider the forest, farmland, grassland, and the migrant population in the inundation area to calculate dam inundation compensation payments. Specific compensation calculations are shown in Table S4.

To minimize environmental harm, we used several environment-based constraints to exclude development in the following: (1) protected areas: World Database of Protected Areas WDPA categories I and II (Strict Nature Reserve, Wilderness Area, and National Park)[52]; (2) UNESCO World Heritage Sites[53]; (3) large lakes: Global Lakes and Wetlands Database, Level 1[54]; (4) high-value (biodiversity, carbon) tropical rainforests[55] and peatlands[56]; and (5) locations where inundation would displace more than 50,000 people[57]. 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 Database[58] to identify locations with "soft" rocks that necessitate higher construction costs to build deeper foundations. To assess the risk of earthquakes, we use the GSHAP Global Seismic Hazard Map[59] 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 PGA larger than 0.7m s^{-1} require more cost to improve the seismic resistance.

(2) Constraints on diversion canal power plants

The most critical parameter of diversion canal power plants is the water intake position, which determines the energy production, as well as the length and diameter of the pipe. To reduce the impact of the diversion canal power plants on the 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 analyzed rivers with a multi-year average discharge of lower than 1,000 m^3 s^{-1} and allocate half of the available discharge that is higher than the environmental flow for electricity generation. Further, the affected streamline and pipe are constrained by not passing through farmland or cities due to excessive costs from disturbance to the supply of agricultural and domestic water demand. The natural river network within 25 kilometers upstream of the virtual hydropower station site is searched to identify a potential water intake. We use the

Dijkstra[60] algorithm to identify the connectivity of the water intake point and the virtual hydropower station site, ensuring connectivity along the river valley.

5. Costs of the hydropower system

In deriving the feasible potential, we use the lowest levelized cost of energy (LCOE) as the evaluation criterion. We base the cost of a hydropower development system on the data from[12,61]. We classify the costs as turbine, power station, electro-technical equipment, fish passage, miscellaneous, power line connection, dam, land loss costs, population displacement compensation, piping-headrace tunnel, and piping-penstock. We also factor in two types of compensation rates: (1) fivefold the local per capita GDP for displaced people[62]; and (2) 475 USD/ha, 10,134 USD/ha, and 3,460 USD/ha, respectively, in cases where virtual reservoirs inundate forests, farmland, and grasslands[63,64]. The global powerline network from OpenStreetMap[37] is used to determine connectance distances from the hydropower system to the power grid by high voltage powerlines. The LCOE has an associated 10% investment rate and a 40-year lifetime. The geometric parameters of the two hydropower systems are determined using terrain analysis (based on constraints of hydropower system simulation). The equations for all components considered are shown in Table S4, and construction cost sensitivity analyses are shown in Text. S3 and Fig. S15.

We calculate the LCOE of different dam heights at each virtual hydropower station site, and select the dam height with the lowest LCOE. We compare the LCOE of different water intakes and select the lowest LCOE as the virtual hydropower station's optimal water intake. If the LCOE is less than 0.5 USD kWh^{-1}, the hydropower system is considered to have feasible potential. If LCOE is less than 0.1 USD kWh^{-1}, the hydropower system is considered to have profitable potential[12].

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 is ranked from smallest to largest 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 does not overlap with the area of existing hydropower systems on the map, the hydropower system is retained. This procedure is repeated until the LCOE of the next hydropower system is considered larger than 0.5 USD kWh^{-1}.

6. Impact analysis

To understand the potential environmental impacts of unused profitable hydropower system sites, we examine the overlaps of reservoir inundation areas with aboveground biomass and the ranges of endangered species. The former is derived from Global Aboveground and Belowground Biomass Carbon Density Maps for the Year 2010 (ref. 65). We calculated the aboveground biomass from the inundated areas of profitable hydropower systems site, and the intensity of aboveground biomass per kilowatt-hour is calculated by dividing the inundated aboveground biomass by the 40-year electricity generation of the hydropower plants:

$$BioEnergy = \frac{B}{40 \times E} \tag{9}$$

where B is the aboveground biomass from the inundated areas of profitable hydropower systems site, E is annual electricity of the profitable hydropower system, and $BioEnergy$ is the intensity of aboveground biomass per kilowatt-hour.

Information on endangered species is derived from the Global Amphibian and Mammal Species Richness Grids of the International Union for Conservation of Nature[66]. We set the endangered species score of hydropower system at 100. According to the endangered species dataset, ten points are deducted for each endangered species in the hydropower plant area; a minimum score of 0 indicates the presence of at least ten endangered species. Then we calculate the endangered species score of the country according to the formula:

$$S = \frac{\sum_{i=1}^{k}(E * S_{danger})}{\sum_{i=1}^{k} E} \tag{10}$$

where S is the country's endangered species score, E is annual electricity 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 (RSR) or species richness (SR) value. We judge whether the hydropower system is located in biodiversity hotspots, then we calculate what percentage of the country's profitable potential is built in biodiversity hotspots according to the formula:

$$S_{hotspot} = \frac{\sum_{i=1}^{k} E_{hotspot}}{\sum_{i=1}^{k} E} \times 100\% \tag{11}$$

where $S_{hotspot}$ is the hydropower potential in biodiversity hotspots percentage of profitable potential, E is annual electricity of the profitable hydropower system, and $E_{hotspot}$ is the profitable hydropower system is 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.

7. Assessment of energy potential at non-powered dams

To assess the global profitable hydropower potential of non-powered dams, we extract the latest global reservoir database from OpenStreetMap[22] (50,591 dams) and the global georeferenced database of dams (GOODD[24], 38,667 dams). We excluded the overlapping dams in the two dam databases and matched them with the global river network dataset. These dams with missing river network information are likely to be located in small streams (considering the 25 km^2 channelization threshold of our river network) and thus have a low potential to produce electricity. Through quality control and spatial matching, we find 29,775 non-powered dams in the global river network (Fig. S9).

Due to the lack of dam height data in the OpenStreetMap and GOODD, we choose dam height data from the U.S. National Inventory of Dams[67] (NID) and exclude the dams that can generate electricity. There are 81,562 dam heights in the NID, of which 76,419 dams are less than 15 meters. We assume that the dam height distribution of global non-powered dams is the same as that of non-powered dams in the United States and use 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 of needed future work. If there is a more complete global reservoir dataset including their associated dam height data available in the future, the profitable hydropower potential assessment of non-powered dams can be more accurate.

Data availability

Discharge dataset are available at http://hydrology.princeton.edu/data/mpan/GRFR/discharge/daily/; River network dataset are available at http://hydrology.princeton.edu/data/mpan/MERIT_Basins/MERIT_Hydro_v07_Basins_v01/; DEM dataset are available at http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_Hydro/; Global Reservoir and Dam Database (GRanD) is available at http://globaldamwatch.org/data/#core_global; the Global Georeferenced Database of Dams (GOODD) is available at http://globaldamwatch.org/data/#core_global; Georeferenced global dam and reservoir (GeoDAR) data are available at https://figshare.com/articles/dataset/Georeferenced_global_Dams_And_Reservoirs_GeoDAR_/13670527; the latest global reservoir dataset and powerline dataset can be extracted from https://www.openstreetmap.org/; the world Database on Protected Areas (WDPA) is available at https://www.protectedplanet.net/en; the natural and mixed world heritage sites are available at https://www.iucn.org/sites/dev/files/import/downloads/natural_and_mixed_world_heritage_sites_2014.kmz; 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/landscan-datasets; 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; International Union for Conservation of Nature (IUCN) Red List data is available at https://www.iucnredlist.org/resources/other-spatial-downloads; the global Amphibian and Mammal Species Richness Grids of the International Union for Conservation of Nature are available at https://sedac.ciesin.columbia.edu/data/set/species-global-mammal-richness-2015; the gross domestic dataset is available at https://datadryad.org/stash/dataset/doi:10.5061/dryad.dk1j0; the global seismic hazard map are available at http://gmo.gfz-potsdam.de/; the global land cover data is available at http://www.esa-landcover-cci.org/?q=node/197; 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 upon request from Z. Zeng.

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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Competing interests statement

The authors declare no competing interests.

Table 1. The theoretical, unused feasible, unused profitable potential and the ratio of the national unused profitable potential to the total electricity generation (P/T) in the main hydropower countries. A ratio exceeding one indicates that the countries unused profitable hydropower could fully satisfy total energy demand. Listed are the top 20 countries with unused profitable hydropower potential. The number in the parentheses stands for the percentage of the world's total potential. The hydropower potential unit is TWh yr^{-1}.

Country	Theoretical potential	Unused potential		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

Figure Legends

Fig. 1. Spatial distribution and cost supply curve of unused profitable potential at the global and continental scales. (**a**) Spatial distribution of unused profitable potential. The profitable potential of each country is calculated based on the hydropower plant location. (**b**) Proportion of theoretical, feasible, and profitable potential of each continent. Both the feasible and profitable potentials account for environmental constraints. (**c**) Cost–supply curves of each continent.

Fig. 2. The national unused profitable potential percentage of total electricity generation.

Fig. 3. The hydropower development stage of each country and continent. The green areas represent a country that hydropower development can be continued, the red areas represent the country's developed hydropower exceeds its full profitable potential, the red shaded areas indicate that the country's developed hydropower has exceeded its full feasible potential. The bar chart represents the full feasible, full profitable, and developed hydropower of each continent, and the unit is TWh yr^{-1}.

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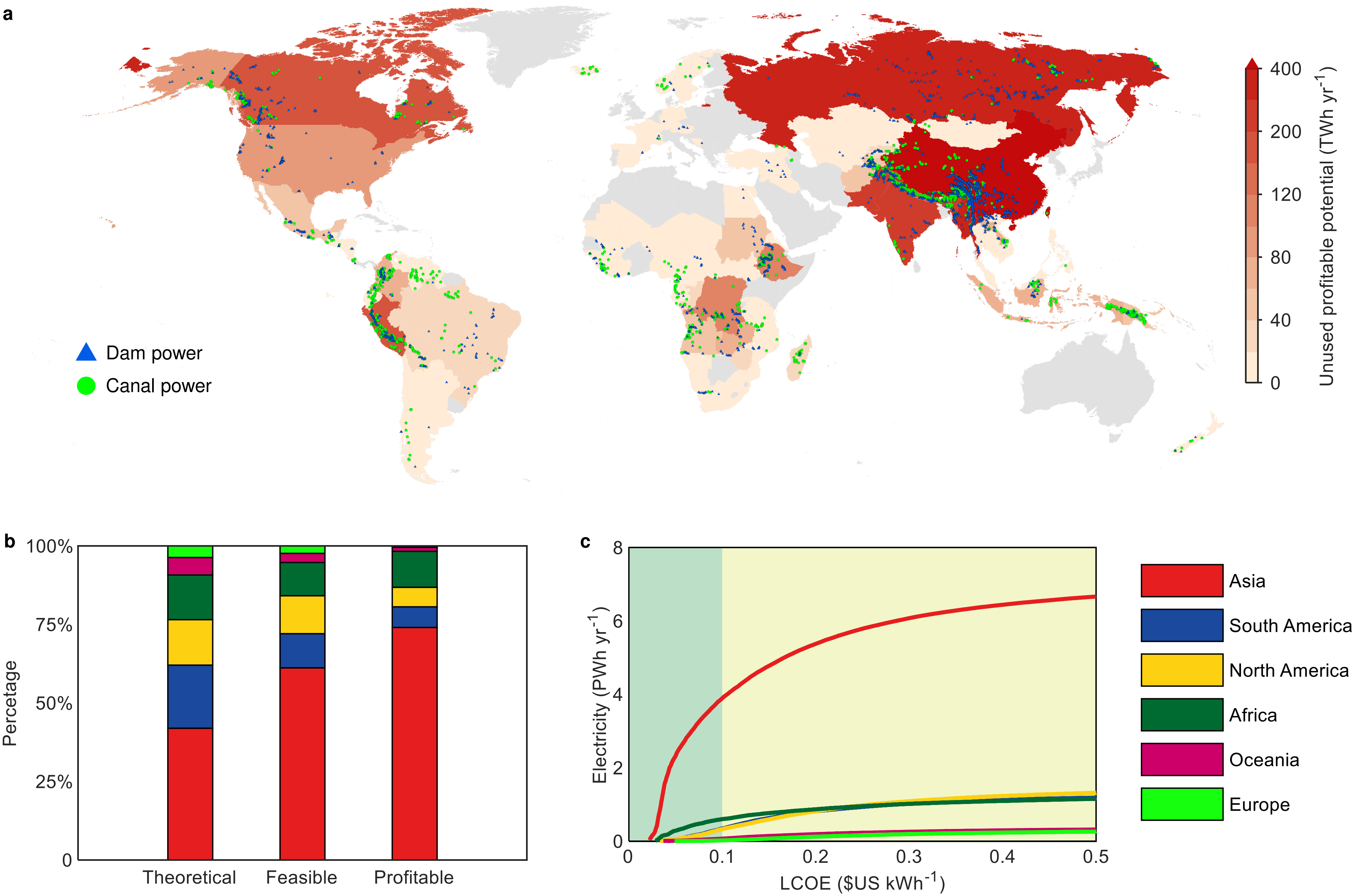
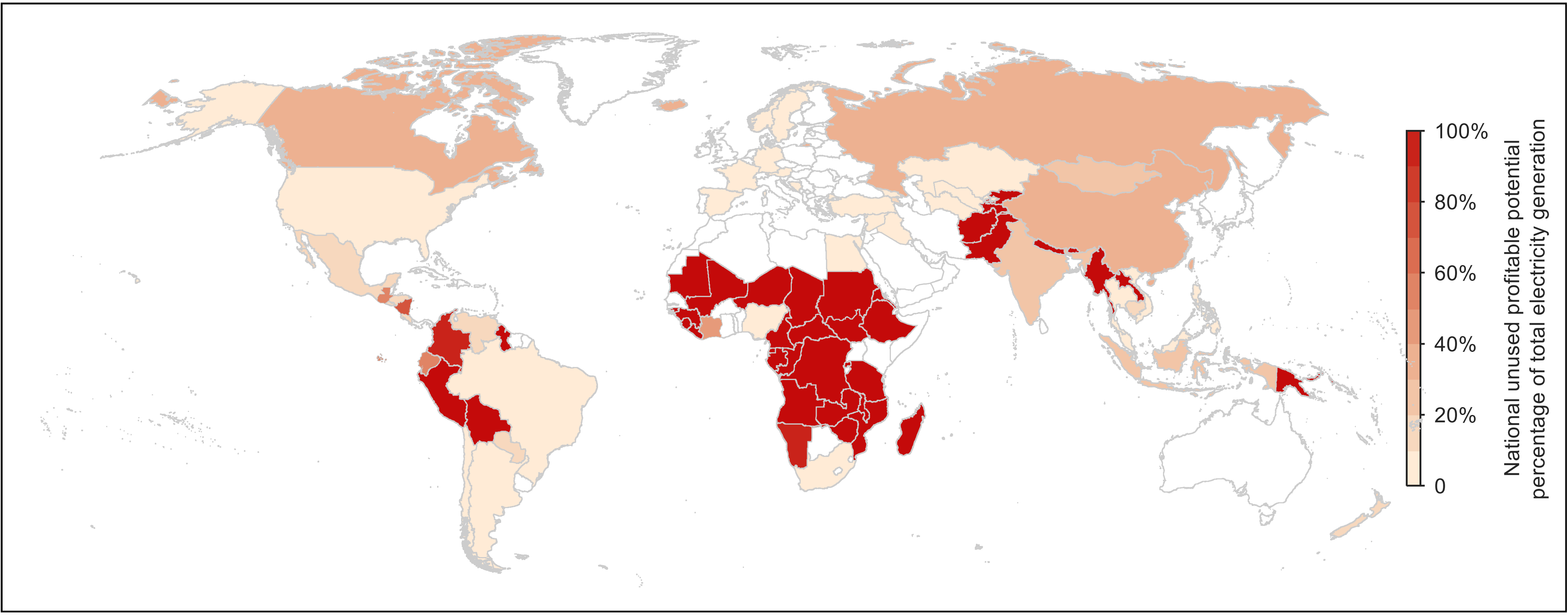
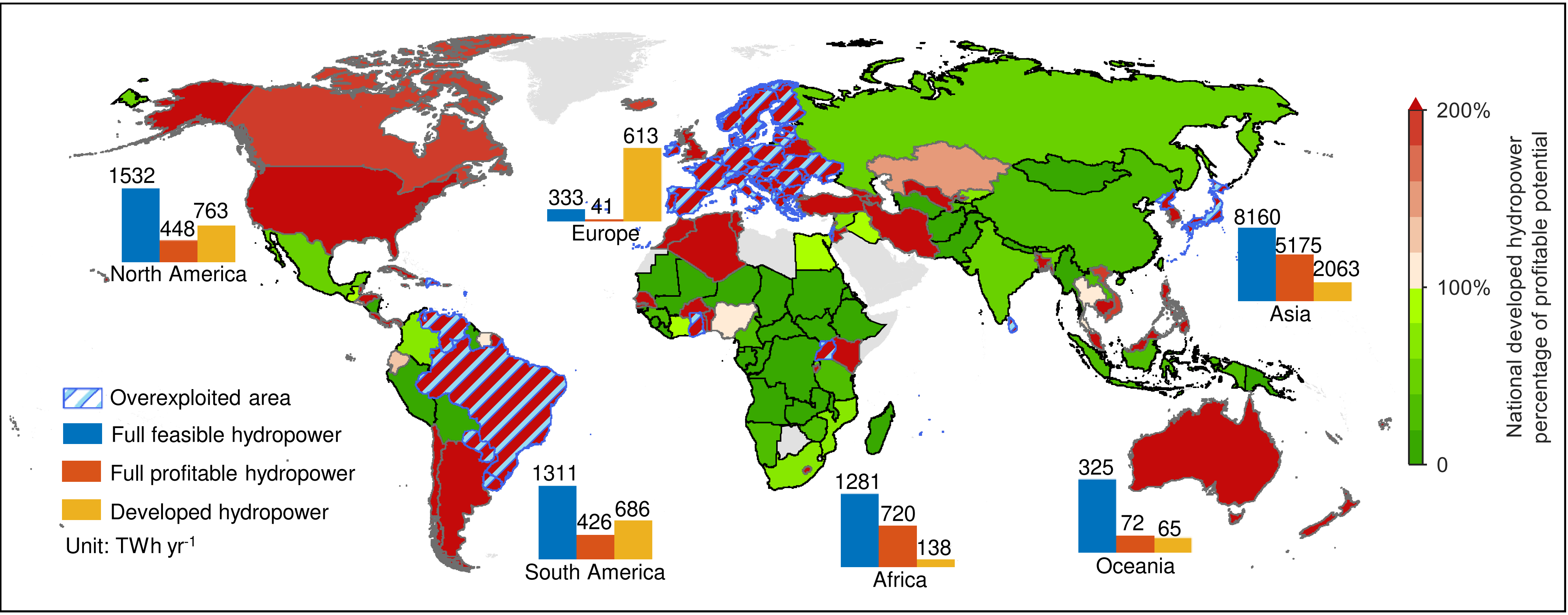

a
400
200
120
80
40
0
Unused profitable potential (TWh yr^{-1})
Dam power
Canal power
b
100%
75%
50%
25%
0
Percetage
Theoretical
Feasible
Profitable
c
8
6
4
2
0
Electricity (PWh yr^{-1})
0
0.1
0.2
0.3
0.4
0.5
LCOE ($US kWh^{-1})
Asia
South America
North America
Africa
Oceania
Europe


100%
80%
60%
40%
20%
0
National unused profitable potential
percentage of total electricity generation


1532
448
763
North America
333
41
613
Europe
8160
5175
2063
Asia
1311
426
686
South America
1281
720
138
Africa
325
72
65
Oceania
Overexploited area
Full feasible hydropower
Full profitable hydropower
Developed hydropower
Unit: TWh yr^{-1}
200%
100%
0
National developed hydropower percentage of profitable potential