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

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39 **The benefits of developing the world's hydropower potential are intensely debated when**
40 **considering the need to avoid or minimize environmental impacts. However, estimates of**
41 **global unused profitable hydropower potential with strict environmental constraints have**
42 **rarely been reported. Here, we perform a global assessment of the unused profitable**
43 **hydropower potential by developing a unified framework that identifies a subset of**
44 **hydropower station locations with reduced environmental impacts on the network of 2.89**
45 **million rivers worldwide. We find that the global unused profitable hydropower potential is**
46 **5.27 PWh yr⁻¹, two-thirds of which is distributed across the Himalayas. Africa's unused**
47 **profitable hydropower is 0.60 PWh yr⁻¹, four times larger than its developed hydropower. By**
48 **contrast, Europe's hydropower potential is extremely exploited. The estimates, developed**
49 **from a consistent and transparent framework, are useful for formulating national**
50 **hydropower development strategies.**

51

52 The development of renewable energy (hydropower, wind power, and photovoltaic power) is
53 increasingly recognized as a crucial step in mitigating global climate change by reducing reliance
54 on fossil fuels¹. Hydropower, in particular, offers a relatively cost-effective energy source that
55 can meet peaks in energy demand on grids with high penetrations of intermittent wind and solar
56 energy^{2,3}. Currently, hydropower contributes 16% of the world's electricity and 69% of all
57 renewable electricity⁴. Looking ahead, hydropower is expected to play a key role in the transition
58 of some nations to decarbonized energy systems. However, the future of global hydropower
59 development is controversial because hydropower systems have many documented negative
60 environmental and societal implications⁵, including the disruption of river ecosystem structure
61 and functioning, obstruction of fish migration routes, the release of greenhouse gases from
62 reservoirs, exacerbation of flood risk via dam failure, land degradation during construction, social
63 displacement, and geopolitical issues⁶⁻⁸. For global society to meet sustainable development goals
64 in the 21st century (in particular SDGs 6, 7, 9, and 13), a unified assessment of global unused
65 profitable hydropower potential that incorporates constraints to reduce environmental and societal
66 impacts is essential.

67 Prior quantitative studies have estimated that the global theoretical hydropower potential
68 ranges from 30.67 to 127.58 PWh per year⁹⁻¹³. Quantifying the unused, economically viable
69 hydropower potential that minimizes some of the associated environmental impacts is
70 challenging, with the wide range of previous estimates encumbered by: (i) low spatiotemporal
71 resolution in hydrological models; (ii) utilization of coarse river network maps that cannot
72 accurately represent river planform geometry and associated environmental conditions; (iii) lack
73 of verification against sufficient river discharge gauge observations, and (iv) incomplete
74 databases listing existing global dams, reservoirs and hydropower plants. Consequently, the
75 locations where new hydropower plants can be built in the future and their associated electricity
76 production potential are not fully understood.

77 Concerning the sustainability of hydroelectricity, prior estimates have rarely incorporated
78 restrictions that limit many negative impacts of hydropower plant construction¹⁴. For example,
79 the most up-to-date estimates made by Gernaat *et al.*¹² only partially considered the
80 environmental costs of hydropower development by incorporating the World Database of
81 Protected Areas (WDPA), but excluded important factors such as tropical forests, peatlands, and
82 biodiversity from consideration. Additionally, environmental flow restrictions need to be
83 considered in greater detail given recent calls for more coherent, multi-objective planning when
84 developing new hydropower infrastructure¹⁵. Also important is the consideration of non-
85 hydropower dams that can be converted to generate hydroelectricity, as well as upgrading
86 existing hydropower dams to maximize full potential^{16,17}. These relatively quick modifications
87 would reduce environmental issues compared with developing new plants. However, since
88 hydropower generation requires high water flow and hydraulic head, it is unclear whether
89 refurbishing non-powered dams is either economically or practically possible.

90 Within the vision to develop the global unused hydropower potential sustainably¹⁸⁻²⁰, we
91 perform a comprehensive analysis by synthesizing fine-resolution river discharge estimates,
92 published reservoir/dam locations, demographic variables, environmental datasets, cost
93 considerations, and strict criteria to limit the environmental and social impact. The analysis is
94 based on reconstructing global naturalized river flows on 2.89 million rivers worldwide (covering
95 60°S to 90°N, excluding Greenland)²¹ to determine locations where new hydropower plants could
96 be established. The discharge dataset is comprehensively evaluated against the daily and monthly
97 flow records of over 14,000 hydrological stations (Fig. S1). For this virtual network, we consider
98 the same two main hydropower systems¹², impoundment (having dams and reservoir) and
99 diversion (having an intake and downstream electricity generation unit), considering their
100 different design criteria and variable impacts on the environment of these two general types of
101 systems. We use the latest global high-resolution MERIT DEM (3 arc-second resolution) and

102 calculations of the Levelized Cost of Energy (LCOE; Fig. S2, see Methods) to determine the
103 optimal type and size of hydropower systems at each potential site in the network.

104 To avoid sensitive locations, we apply strict criteria to limit environmental and social
105 impacts. For example, we directly exclude hydropower plant development in heritage areas,
106 biodiversity hotspots, forests, peatlands, earthquake-prone zones, densely populated areas, and
107 locations where dams/reservoirs already exist. To generate a new reservoir dataset that includes
108 data for all installed hydropower plants worldwide, we integrate global reservoir datasets (e.g.,
109 OpenStreetMap²², GRanD²³, GOODD²⁴, and GeoDAR²⁵) and include a total of 445,669
110 reservoirs in our assessment (see Methods). Importantly, we stipulate that a new hydropower
111 station must maintain an environmental flow that will support downstream river ecosystem
112 integrity and water availability during baseflow conditions, particularly within dry seasons. In
113 cases where sites identified for hydropower expansion are too closely situated, we retain the one
114 with the lowest LCOE (Fig. S2). Collectively, this approaches us to estimate the unused feasible
115 and profitable hydropower potential to be developed worldwide (definitions in Table S1, Fig. S2).
116 Finally, we identify 124,761 unused feasible hydropower system sites worldwide, among which
117 4,644 sites are profitable (see Methods).

118 Our assessment reveals that the baseline global theoretical hydropower potential is 57.9
119 PWh yr⁻¹ (Fig. S3; Text. S1), slightly higher than the two most recent estimates of 50-52 PWh yr⁻¹
120 ^{ref.12,13}. We estimated the global unused feasible and profitable hydropower potential is 10.89
121 PWh yr⁻¹ and 5.27 PWh yr⁻¹, respectively. The global profitable hydropower potential has an
122 upward trend, with an annual increase of 0.008 PWh yr⁻¹ from 1979 to 2016 (Fig. S4). However,
123 the spatial distribution of global hydropower profitable potential trends is different. The profitable
124 potential in Canada, Russia, Andes, southern Africa, Indonesia, and Papua New Guinea has
125 increased over the past 40 years, while profitable potential in the western United States, Europe
126 and Central Africa has decreased (Fig. S5). Furthermore, future climate change can increase or
127 decrease hydropower production through changes in precipitation, evaporation, glacier melt,

128 sediment load, and extreme cascading hazards, but these changes and their impacts on the global
129 profitable hydropower potential is extremely challenging to be quantified^{26,27}. Regional power
130 grid interconnection can mitigate climate impacts on hydropower²⁸. Thus, future studies and
131 hydropower policy development also need to address climate change impacts on a case-by-case
132 basis.

133 In our analysis, impoundment power plants account for 81% of the global unused profitable
134 potential, compared with 19% for diversion hydropower plants. The multi-year mean discharge at
135 most impoundment power plants ranges between 100 and 1,200 m³ s⁻¹, compared with 10 to 150
136 m³ s⁻¹ for diversion plants (Fig. S6). Most of these hydropower systems identified in our analysis
137 have installed capacities between 100 MW and 650 MW, but some have capacities less than 50
138 MW (Fig. S7). Few small plants are identified in our approach because they were either not cost-
139 effective (high LCOE), could not be designed to ensure sufficient environmental flows could be
140 maintained, or they would have encroached on sensitive areas, particularly forests. The small
141 diversion hydropower plants in the Himalayas and the Andes are appropriate to include tributary
142 streams that steep relief allows sufficient fall heights to generate electricity efficiently. Contrary
143 to ongoing development (e.g., in Vietnam), our analysis does not support small diversion plant
144 development on tiny headwater streams because of their impact on the environment and
145 economic costs. Our analysis does indicate that Iceland, Norway, and Papua New Guinea could
146 also potentially support profitable networks of diversion hydropower systems (Fig. 1a).

147 Our assessment is quite different to that of Gernaat *et al.*¹² due to the enhanced level of
148 environmental constraints, our identification of substantially more existing dams and/or
149 reservoirs, and more accurate discharge datasets to inform modeling. Notably, Asia's unused
150 profitable potential (3.90 PWh yr⁻¹) is three times greater than the prior estimate¹⁰. While the
151 spatial distribution of unused profitable hydropower sites in high-mountain Asia is roughly
152 consistent with the prior assessment, the energy production cost is much lower in the high-relief
153 Himalaya than in other parts of the world (Fig. 1c), leading to our finding of a greater profitable

154 potential than estimated before. Africa ranks second with a total of 0.60 PWh yr⁻¹ unused
155 profitable hydropower potential. Together, Asia and Africa account for 85% of the global unused
156 profitable potential (Fig. 1b), mostly in China, Myanmar, India, Pakistan, Nepal of Asia, and D.R.
157 Congo, Ethiopia, and Zambia in Africa (Table 1, Table S2). North America and South America,
158 which have similar cost supply curves, and their unused profitable potential is 0.33 PWh yr⁻¹ and
159 0.34 PWh yr⁻¹, respectively. South America has high theoretical hydropower generation potential,
160 but our requirement to conserve tropical forest reduces both the feasible and profitable potential
161 values greatly²⁹. Therefore, our estimate for South America's unused profitable potential is less
162 than half of that by Gernaat *et al.*¹², which did not considered the conservation of tropical forests.
163 Oceania and Europe have limited unused profitable potential (Fig. 1c). We further find that
164 Europe's unused profitable potential is only one-seventh that of Gernaat *et al.*¹², largely because
165 we impose stringent environmental flow restrictions on the power generation of diversion canal
166 power plants.

167 At the level of individual countries, China has the highest existing hydropower production
168 (~1.23 PWh in 2021)⁴; also has the world's largest unused profitable potential (Table 1). Potential
169 development sites are concentrated mainly in the mountaious provinces of Tibet, Sichuan,
170 Yunnan, and Guizhou (Fig. 1a). This unused profitable potential hydropower of 2.25 PWh yr⁻¹
171 could meet 30% of China's current electricity demand of 7.19 PWh yr⁻¹. Myanmar, Russia, India,
172 and Pakistan also have unused profitable potentials in the 210-340 TWh yr⁻¹ (Fig. 1a; Table 1). In
173 addition, among the top 20 countries with unused profitable hydropower potential, Myanmar,
174 Pakistan, Peru, Nepal, D.R. Congo, Ethiopia, and Laos could fully meet their total current
175 electricity demand by developing the unused profitable hydropower resources (Table 1).
176 Meanwhile, Africa's current hydropower generation is 0.14 PWh yr⁻¹, much less than its unused
177 profitable potential (*i.e.*, 0.60 PWh yr⁻¹), indicating that hydropower development on the
178 continent is still in its infancy. Most African countries could potentially fully meet their current
179 electricity demand if they were to develop their unused profitable potential (Fig. 2), which can

180 significantly improve Africa's infrastructure and energy situation. Currently, only Mozambique,
181 Zambia, Ethiopia, Egypt, and DR Congo rank in the top 50 worldwide in hydropower generation,
182 ranging from about 11 to 14 TWh yr⁻¹.

183 Uprating existing non-powered dams can also increase electricity generation¹⁷. We estimate
184 that the profitable hydropower potential of refurbishing non-powered dams is only 0.23 [0.07,
185 0.62] PWh yr⁻¹ (Fig. S8; see Methods). This estimate is underestimated as it is based on only
186 29,775 non-powered dams in the global river network (Fig. S9). However, the true value may not
187 be substantially higher than our crude estimate because these types of dams tend to be located on
188 river sections where mean discharge is relatively low. Most (92%) of the multi-year mean
189 discharge value of the rivers where the non-powered dams are located is below 50 m³ s⁻¹, which
190 is lower than the 100 and 1,200 m³ s⁻¹ range associated with most of our hydropower systems in
191 the virtual network that produce the estimated undeveloped profitable potential (Fig. S6).
192 Hydropower development via impoundment structures in locations with relatively low discharge
193 is often not cost-effective from the perspective of LCOE. Nevertheless, the uncertainty associated
194 with this particular contribution to hydropower potential is an area of needed future work.

195 One of the greatest challenges for decarbonization is addressing the difficulty in maintaining
196 power grid stability given the unbalance between fluctuating power demand and real-time
197 electricity production by renewable sources³⁰. Pumped hydro energy storage (PHS) is a tested
198 technology with great potential for worldwide development³¹. Potential river power plants sites
199 with large reservoirs may in some cases, be suitable for pumped storage plants. According to the
200 global atlas of closed-loop pumped hydro energy storage³², we find that there are 1,214 river
201 power plants globally that overlap with pumped hydropower resources (Fig. S10). The future
202 hydropower plants can be potentially situated strategically to leverage this capacity to both
203 generate and store energy efficiently³³.

204 Whilst our quantitative framework set many constraints to minimize the environmental and
205 social displacements associated with hydropower development, developing the unused profitable

206 hydropower system sites will likely lead to some type of impact. For example, hydropower
207 development fundamentally changes the natural discharge of rivers, disturbs freshwater
208 ecosystems, and may contribute to local species extinctions⁷. To address this issue, we disallow
209 development in many sensitive areas and require that environmental flows be maintained to
210 preserve ecosystem functioning in rivers (see Table S3 for a comparison of flow scenarios).
211 Globally, the criteria to maintain critical stream discharges significantly impact profitable
212 hydropower potential (Text S2, Fig. S11). If no environmental flow criteria are used, global
213 profitable potential could be as high as 10.48 PWh yr⁻¹ because maximal volumes of water are
214 stored and/or diverted to produce hydroelectricity. In contrast, maintaining 90% of the multi-year
215 average river discharge at each hydropower site would decrease the potential to 1.94 PWh yr⁻¹. In
216 comparison, our conservative criteria of Q30 (30th percentile of all daily flows in the 38-year
217 dataset) lead to the estimate of 5.27 PWh yr⁻¹ profitable potential. Other commonly used flow
218 criteria, such as the Tennant and Tessmann methods¹³ produce slightly higher estimates: 6.26
219 PWh yr⁻¹ and 5.58 PWh yr⁻¹, respectively (Text S2; Fig. S11). Maintaining critical flows is
220 essential in regions such as Southeast Asia, where many globally-important biodiversity hotspots
221 exist (Fig. S12). Thus, we anticipate that large tradeoffs will be needed to support both
222 environmental conservation and hydropower development throughout the region. It will also
223 affect the hydropower potential assessment. This situation is now quite controversial on within
224 the Mekong River Basin³⁴.

225 We also find that the aboveground biomass losses associated with developing the global
226 unused profitable hydropower system sites to be 0.143 PgC, mainly distributed in Asia (0.060
227 PgC) and North America (0.032 PgC). Globally, the carbon emission intensity of these
228 hydropower system sites is only 0.68 g kWh⁻¹, which is much lower than the carbon emission
229 intensity of coal thermal power plants of 180 g kWh⁻¹ ref.³⁵. We estimated that the development of
230 all unused profitable hydropower sites would produce renewable energy with an associated
231 carbon loss equivalent to 3.4 billion tons of CO₂ emissions per year, or about 8.2% of the current

232 annual anthropogenic carbon dioxide emissions³⁶. Regionally, the largest inundated aboveground
233 biomass is in Russia (27 TgC), followed by Canada (26 TgC), Myanmar (12 TgC), and China (11
234 TgC). China has a high unused profitable hydropower system sites inundate few forests and
235 wetlands because hydropower generation is highly efficient in the steep terrain of the Himalaya.
236 The carbon emission intensity in China is only 0.13 g kWh⁻¹ (Fig. S13). Brazil has the highest
237 inundated aboveground biomass loss per kilowatt-hour associated with developing its unused
238 profitable potential (7.3 g kWh⁻¹), despite our approach being designed to avoid tropical forests.

239 Concerning societal impacts, we further estimate that the total displacement of people
240 associated with the development of global unused profitable hydropower system sites is
241 approximately 650 thousand people, less than the 1.3 million displaced when the Three Gorges
242 Dam was constructed³⁷. Our approach excludes locations where inundation would displace more
243 than 50,000 people. This reasonable site selection strategy effectively reduced the human
244 displacement in our analysis. To test the sensitivity of the hydropower potential to the magnitude
245 of the displacement threshold, we vary the reservoir displacement threshold from 0 to 50,000
246 people and re-quantify the global unused profitable potential. When any displacement is not
247 allowed, we find that the unused profitable potential is only 2.26 PWh yr⁻¹. However, when the
248 displacement threshold reaches 100 people, there is almost no impact on the unused profitable
249 potential (Fig. S14). Thus, a much more conservative displacement threshold can be applied, but
250 caution is needed in applying any criteria of this nature because all rural and transient populations
251 may not be accurately represented in published demographic databases. Further, the loss of
252 productive lands needs to be factored fully into the compensations. In our assessment, we
253 stipulated that the compensation for displacement would have a value equivalent to five-fold the
254 local per capita GDP; and we compensated for the loss of agricultural lands, forests, and
255 grasslands. Compensation increases the cost of energy production, affecting which sites are
256 deemed profitable or feasible.

257 Our estimate of the global unused profitable potential excludes areas with existing
258 reservoirs. Here, a full potential scenario is produced by removing this constraint and re-
259 quantifying the hydropower potential of each country (Fig. S2). By comparing the full feasible
260 (profitable) hydropower potential with developed hydropower data from the IEA's generation
261 dataset⁴, we are able to assess the national hydropower development stage of each country.
262 Specifically, if a country's hydropower generation exceeds its full feasible potential, we define it
263 as an overexploited development. Globally, the world's hydropower generation in 2018 was 4.32
264 PWh, less than our estimate of the world's full profitable potential (6.87 PWh yr⁻¹). However, the
265 world's hydropower development stage shows substantial regional imbalance (Fig. 3).

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

281 Many countries in Asia and Africa have also not maximized their profitable hydropower
282 potentials. Specifically, the Himalayas, Asia's water tower, have the greatest potential for

283 hydropower expansion, and many planned reservoirs are already underway in the region⁴³. As
284 this region includes the world's largest transboundary river basin (Brahmaputra), China, India,
285 Bhutan, and Bangladesh need to strengthen cooperation in hydropower development and river
286 flow management⁴⁴. Such strong cooperation is needed for all international rivers worldwide to
287 avoid conflicts. In addition, with climate change accelerating the melting of glaciers⁴⁵, there is
288 likely to be a need to build more reservoirs to withstand the floods and maintain water supply
289 year-round^{46,47} – but this approach must be balanced with the risks of outburst floods occurring
290 on dammed rivers. Additionally, much of the world's population growth may occur in Africa
291 where hydropower development has not been substantial to date. Given the need to improve on
292 all types of security (food, water, energy, livelihood), hydropower systems that can be developed
293 on multi-functional reservoirs could be prioritized if they can be developed sustainably⁵. With
294 regard to efficient and sustainable energy production, multi-functionality could apply to
295 combining traditional hydropower generation, pumped storage, and floating photovoltaic
296 systems.

297 Our approach of using a consistent and transparent framework to analyze hydropower
298 development potential indicates that the global unused profitable hydropower potential is 5.27
299 PWh yr⁻¹, which is 60% higher than the recent estimate made by Gernaat *et al.*¹². Through
300 reasonable hydropower development, the global hydropower capacity could double to 9 PWh yr⁻¹,
301 implying that hydropower could occupy a larger role in the future energy-resource structure⁴⁸.
302 Most of these undeveloped hydropower system sites are located in the highlands of Asia,
303 particularly in China, with substantial potential remaining in Africa and other locations with high
304 mountain chains. Many countries in developing regions are anticipated to experience substantial
305 population and infrastructural growth in the future, hydropower development can potentially play
306 a key role in their overall development goals. Complicating the issue of harnessing this unused
307 profitable hydropower potential is managing river flows to preserve the environment, people's
308 livelihoods, and geopolitical stability. Our quantitative framework to assess hydropower potential

309 offers a means to guide decision-making toward achieving Sustainable Development Goals. As
310 such, hydropower development worldwide could proceed with fewer negative environmental and
311 social impacts than in the past.

312

313

314 **Methods**

315 1. Discharge dataset

316 Our estimate of hydropower potential using the 38 years (1979-2016) global runoff dataset
317 from the Terrestrial Hydrology Research Group at Princeton University¹⁷ contains discharge
318 information on 2.89 million rivers globally. It vectorizes the global river network by the latest
319 global high-resolution MERIT DEM^{49,50} (3" resolution, or ~90 m at the equator), producing
320 modeled river routes consistent with satellite-based information. The product provides 0.05° daily
321 river discharge records for 2.89 million global rivers for 38 years (1979-2016). The records are
322 produced using the Variable Infiltration Capacity (VIC) land surface model and Routing
323 Application for Parallel computation of Discharge (RAPID) river routing model. Precipitation
324 forcing is from a 0.1° global product that merged gauge-, reanalysis-, and satellite-based data⁵¹.
325 Runoff simulations are constrained using a set of machine learning-derived, global runoff
326 characteristics map for the grid by grid model calibration and bias correction. Daily and monthly
327 observations from more than 14,000 sites are used for validation. More than half (59%) of the
328 stations' multi-year mean discharge simulation relative errors are within 20%, and 80% of the
329 stations' relative error is within 40% (Fig. S1). To be consistent with the discharge dataset, we use
330 MERIT Basins²¹ and Hydrologically Adjusted Elevations from MERIT Hydro as the river
331 network dataset and DEM dataset⁵⁰ from which other geographical information is derived
332 regarding hydropower plant construction (e.g., dam location/width; diversion canal/tunnel
333 placement; inundation area) and impact.

334

335 2. Reservoir datasets

336 To generate a new reservoir dataset that includes the data of all installed hydropower plants
337 in the world as much as possible, we first extract the latest global reservoir database from
338 OpenStreetMap²², including 50,591 dams and 425,455 reservoirs globally. Next, we integrate the
339 database with the previous three global reservoir datasets: GRanD²³, GOODD²⁴, and GeoDAR²⁵.

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

344

345 3. Hydropower potential calculations

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

$$347 \quad E_T = 9.81HQ \quad (1)$$

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

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

$$352 \quad E_T = 9.81H\bar{Q} \times 24 \times 365 \quad (2)$$

353 As a baseline, we first calculate the theoretical hydropower potential for each country. Since
354 a large portion of the energy of the natural river are dissipated by friction, we need to build
355 hydropower plants to reduce hydraulic head loss. Due to the high hydropower plant cost, our
356 assessment distinguishes feasible and profitable potential (definitions in Table S1, Fig. S2). We
357 model the establishment of virtual hydropower system sites at an interval of 4.5 km for 2.89
358 million rivers worldwide (a total of 4.14 million sites) and quantify the feasible and profitable
359 potential of hydropower at each site.

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

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

$$370 \quad E_E = \sum_t 9.81 \times \min(Q_t, Q_D) H_D \eta / N \quad (3)$$

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

$$373 \quad Q_t = \max(Q - Q_{eflow}, 0) \quad (4)$$

374 For diversion canal power plants:

$$375 \quad Q_t = 0.5 \times \max(Q - Q_{eflow}, 0) \quad (5)$$

376 In Equations 4 and 5, Q is the discharge of the river, and Q_{eflow} is 30th-percentile of daily
 377 discharge during the 38-year period, which is a relatively conservative estimate of profitable
 378 potential (Text. S2, Fig. S15). To make full use of hydropower, Q_D in Equation 3 incorporates
 379 the 97th-percentile of Q_t recorded during the 38-year period. The term η is the efficiency of
 380 river power plants (0.7) or the diversion canal power plants (0.9)¹². For river power plants, H_D is
 381 the dam height, and for diversion canal power plants, H_D is calculated as:

$$382 \quad H_D = H_G - h_f \quad (6)$$

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

$$385 \quad h_f = \lambda \frac{l v^2}{d 2g} \quad (7)$$

386 where l is the pipe length (m), d is the pipe diameter, g is the gravitational acceleration, and v
 387 is the water velocity in a pipe. We use the Blasius equations to calculate λ from the Reynolds
 388 number:

$$389 \quad \lambda = 0.316 Re^{-0.25} \quad (8)$$

390

391 4. Constraints on hydropower system simulation

392 4.1 Constraints on river power plants

393 The dam height is the most critical parameter of river power plants as it is fundamental to
394 the determination of energy production, dam cost, compensation for flooded farmland, population
395 displacement, and various other environmental impacts. We parameterize the dam height from 10
396 to 300 meters in the construction of dams at virtual sites¹² Dams are virtually built in two
397 directions, east-west and north-south to calculate how wide the dam would need to be to block the
398 valley completely. We choose the smaller width of the dam in the two directions as the
399 construction direction. If the dam's width is greater than 3,000 meters in both directions, this dam
400 height of the virtual site is discarded.

401 To determine the direction of inundation after constructing the dam at the virtual site, we
402 identify the upstream and downstream segments of the river using the DEM and simulate the
403 inundation area by setting the virtual hydropower plant location as the starting inundation point.
404 Points with DEM values lower than the virtual site's DEM value plus the dam height are selected
405 gradually upstream along the inundation direction. Each new inundated point had to be connected
406 with existing inundation points to ensure the continuity of the inundation area. The search
407 continues until no point's DEM value is lower than the virtual site's DEM plus dam height. In this
408 way, we can determine the inundation area¹². However, if the inundation area already had a
409 reservoir (based on the reservoir datasets) or the environmental impact is deemed too negative
410 (based on constraints below), dam construction at that location is removed from the model.
411 Further, to reduce the impact of reservoir migration, the inundation area's population is must less
412 than 50,000 people, otherwise the site is excluded. While ensuring water reliability, the
413 reservoir's volume should be less than the two-year total discharge of the river. Meanwhile, we
414 consider the forest, farmland, grassland, and the migrant population in the inundation area to
415 calculate dam inundation compensation payments. Specific compensation calculations are shown
416 in Table S4.

417 To minimize environmental harm, we used several environment-based constraints to exclude
418 development in the following: (1) protected areas: World Database of Protected Areas WDPA
419 categories I and II (Strict Nature Reserve, Wilderness Area, and National Park)⁵²; (2) UNESCO
420 World Heritage Sites⁵³; (3) large lakes: Global Lakes and Wetlands Database, Level 1⁵⁴; (4) high-
421 value (biodiversity, carbon) tropical rainforests⁵⁵ and peatlands⁵⁶; and (5) locations where
422 inundation would displace more than 50,000 people⁵⁷. We also considered various economic
423 constraints associated with construction in areas with complex geology and seismic hazards. For
424 the former, we used the Harmonized World Soil Database⁵⁸ to identify locations with "soft" rocks
425 that necessitate higher construction costs to build deeper foundations. To assess the risk of
426 earthquakes, we use the GSHAP Global Seismic Hazard Map⁵⁹ which depicts the seismic hazard
427 as Peak Ground Acceleration (PGA) with a 10% probability of exceedance in 50 years,
428 corresponding to a return period of 475 years. Locations with PGA larger than 0.7 m s^{-1} require
429 more cost to improve the seismic resistance.

430

431 (2) Constraints on diversion canal power plants

432 The most critical parameter of diversion canal power plants is the water intake position,
433 which determines the energy production, as well as the length and diameter of the pipe. To reduce
434 the impact of the diversion canal power plants on the river network's natural topology, upstream
435 water intake and the virtual site have to be connected in a natural river network to ensure that the
436 diversion hydropower station only affects the inlet and outlet section of the river flow.
437 Meanwhile, we only analyzed rivers with a multi-year average discharge of lower than $1,000 \text{ m}^3$
438 s^{-1} and allocate half of the available discharge that is higher than the environmental flow for
439 electricity generation. Further, the affected streamline and pipe are constrained by not passing
440 through farmland or cities due to excessive costs from disturbance to the supply of agricultural
441 and domestic water demand. The natural river network within 25 kilometers upstream of the
442 virtual hydropower station site is searched to identify a potential water intake. We use the

443 Dijkstra⁶⁰ algorithm to identify the connectivity of the water intake point and the virtual
444 hydropower station site, ensuring connectivity along the river valley.

445

446 5. Costs of the hydropower system

447 In deriving the feasible potential, we use the lowest levelized cost of energy (LCOE) as the
448 evaluation criterion. We base the cost of a hydropower development system on the data from^{12,61}.
449 We classify the costs as turbine, power station, electro-technical equipment, fish passage,
450 miscellaneous, power line connection, dam, land loss costs, population displacement
451 compensation, piping-headrace tunnel, and piping-penstock. We also factor in two types of
452 compensation rates: (1) fivefold the local per capita GDP for displaced people⁶²; and (2) 475
453 USD/ha, 10,134 USD/ha, and 3,460 USD/ha, respectively, in cases where virtual reservoirs
454 inundate forests, farmland, and grasslands^{63,64}. The global powerline network from
455 OpenStreetMap³⁷ is used to determine connectance distances from the hydropower system to the
456 power grid by high voltage powerlines. The LCOE has an associated 10% investment rate and a
457 40-year lifetime. The geometric parameters of the two hydropower systems are determined using
458 terrain analysis (based on constraints of hydropower system simulation). The equations for all
459 components considered are shown in Table S4, and construction cost sensitivity analyses are
460 shown in Text. S3 and Fig. S15.

461 We calculate the LCOE of different dam heights at each virtual hydropower station site, and
462 select the dam height with the lowest LCOE. We compare the LCOE of different water intakes
463 and select the lowest LCOE as the virtual hydropower station's optimal water intake. If the LCOE
464 is less than 0.5 USD kWh⁻¹, the hydropower system is considered to have feasible potential. If
465 LCOE is less than 0.1 USD kWh⁻¹, the hydropower system is considered to have profitable
466 potential¹².

467 Due to the high-density sampling of the river network, the hydropower systems at different
468 virtual sites could potentially overlap spatially. To avoid this problem, the LCOE of each

469 hydropower system is ranked from smallest to largest then sequentially we added virtual
470 hydropower plants into an empty global map starting with the lowest LCOE plant. If the area of
471 the hydropower system to be placed on the map at each step does not overlap with the area of
472 existing hydropower systems on the map, the hydropower system is retained. This procedure is
473 repeated until the LCOE of the next hydropower system is considered larger than 0.5 USD kWh⁻¹.

474

475 6. Impact analysis

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

$$483 \quad BioEnergy = \frac{B}{40 \times E} \quad (9)$$

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

487 Information on endangered species is derived from the Global Amphibian and Mammal
488 Species Richness Grids of the International Union for Conservation of Nature⁶⁶. We set the
489 endangered species score of hydropower system at 100. According to the endangered species
490 dataset, ten points are deducted for each endangered species in the hydropower plant area; a
491 minimum score of 0 indicates the presence of at least ten endangered species. Then we calculate
492 the endangered species score of the country according to the formula:

$$493 \quad S = \frac{\sum_{i=1}^k (E * S_{danger})}{\sum_{i=1}^k E} \quad (10)$$

494 where S is the country's endangered species score, E is annual electricity of the profitable
495 hydropower system, and S_{danger} is the endangered species score of the profitable hydropower
496 system site.

497 We identified biodiversity hotspots using two species pools: all species belonging to any
498 International Union for Conservation of Nature (IUCN) Red List category; and threatened species
499 listed as CR (Critically Endangered), EN (Endangered) and VU (Vulnerable) on the IUCN Red
500 List (available at <https://www.iucnredlist.org/resources/other-spatial-downloads>). We define
501 biodiversity hotspots as the upper 2.5% of grid cells with the highest range-size rarity (RSR) or
502 species richness (SR) value. We judge whether the hydropower system is located in biodiversity
503 hotspots, then we calculate what percentage of the country's profitable potential is built in
504 biodiversity hotspots according to the formula:

$$505 \quad S_{hotspot} = \frac{\sum_{i=1}^k E_{hotspot}}{\sum_{i=1}^k E} \times 100\% \quad (11)$$

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

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

512

513 7. Assessment of energy potential at non-powered dams

514 To assess the global profitable hydropower potential of non-powered dams, we extract the
515 latest global reservoir database from OpenStreetMap²² (50,591 dams) and the global
516 georeferenced database of dams (GOODD²⁴, 38,667 dams). We excluded the overlapping dams in
517 the two dam databases and matched them with the global river network dataset. These dams with
518 missing river network information are likely to be located in small streams (considering the 25
519 km² channelization threshold of our river network) and thus have a low potential to produce

520 electricity. Through quality control and spatial matching, we find 29,775 non-powered dams in
521 the global river network (Fig. S9).

522 Due to the lack of dam height data in the OpenStreetMap and GOODD, we choose dam
523 height data from the U.S. National Inventory of Dams⁶⁷ (NID) and exclude the dams that can
524 generate electricity. There are 81,562 dam heights in the NID, of which 76,419 dams are less than
525 15 meters. We assume that the dam height distribution of global non-powered dams is the same
526 as that of non-powered dams in the United States and use the Monte Carlo method to simulate the
527 dam height of global non-powered dams. Nevertheless, the uncertainty associated with this
528 contribution to hydropower potential is an area of needed future work. If there is a more complete
529 global reservoir dataset including their associated dam height data available in the future, the
530 profitable hydropower potential assessment of non-powered dams can be more accurate.

531

532

533 **Data availability**

534 Discharge dataset are available at
535 <http://hydrology.princeton.edu/data/mpan/GRFR/discharge/daily/>; River network dataset are
536 available at
537 http://hydrology.princeton.edu/data/mpan/MERIT_Basins/MERIT_Hydro_v07_Basins_v01/;
538 DEM dataset are available at http://hydro.iis.u-tokyo.ac.jp/~yamadai/MERIT_Hydro/; Global
539 Reservoir and Dam Database (GRanD) is available at
540 http://globaldamwatch.org/data/#core_global; the Global Georeferenced Database of Dams
541 (GOODD) is available at http://globaldamwatch.org/data/#core_global; Georeferenced global dam
542 and reservoir (GeoDAR) data are available at
543 [https://figshare.com/articles/dataset/Georeferenced_global_Dams_And_Reservoirs_GeoDAR_/13](https://figshare.com/articles/dataset/Georeferenced_global_Dams_And_Reservoirs_GeoDAR_/13670527)
544 [670527](https://figshare.com/articles/dataset/Georeferenced_global_Dams_And_Reservoirs_GeoDAR_/13670527); the latest global reservoir dataset and powerline dataset can be extracted from
545 <https://www.openstreetmap.org/>; the world Database on Protected Areas (WDPA) is available at
546 <https://www.protectedplanet.net/en>; the natural and mixed world heritage sites are available at
547 [https://www.iucn.org/sites/dev/files/import/downloads/natural_and_mixed_world_heritage_sites_](https://www.iucn.org/sites/dev/files/import/downloads/natural_and_mixed_world_heritage_sites_2014.kmz)
548 [2014.kmz](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-](https://www.worldwildlife.org/pages/global-lakes-and-wetlands-database)
549 [wetlands-database](https://www.worldwildlife.org/pages/global-lakes-and-wetlands-database); the tropical rainforests dataset is available at
550 <https://glad.umd.edu/dataset/primary-forest-humid-tropics>; the peatlands dataset is available at
551 <https://archive.researchdata.leeds.ac.uk/251/>; the population dataset is available at
552 <https://landscan.ornl.gov/landscan-datasets>; the electricity consumption dataset is available at
553 [https://www.iea.org/data-and-statistics/data-](https://www.iea.org/data-and-statistics/data-browser/?country=WORLD&fuel=Energy%20consumption&indicator=TotElecCons)
554 [browser/?country=WORLD&fuel=Energy%20consumption&indicator=TotElecCons](https://www.iea.org/data-and-statistics/data-browser/?country=WORLD&fuel=Energy%20consumption&indicator=TotElecCons); the
555 electricity supply dataset is available at [https://www.iea.org/data-and-statistics/data-](https://www.iea.org/data-and-statistics/data-browser/?country=WORLD&fuel=Energy%20supply&indicator=ElecGenByFuel)
556 [browser/?country=WORLD&fuel=Energy%20supply&indicator=ElecGenByFuel](https://www.iea.org/data-and-statistics/data-browser/?country=WORLD&fuel=Energy%20supply&indicator=ElecGenByFuel); the global
557 aboveground biomass carbon density maps are available at [https://daac.ornl.gov/cgi-](https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1763)
558 [bin/dsviewer.pl?ds_id=1763](https://daac.ornl.gov/cgi-bin/dsviewer.pl?ds_id=1763); International Union for Conservation of Nature (IUCN) Red List data

559 is available at <https://www.iucnredlist.org/resources/other-spatial-downloads>; the global
560 Amphibian and Mammal Species Richness Grids of the International Union for Conservation of
561 Nature are available at [https://sedac.ciesin.columbia.edu/data/set/species-global-mammal-
562 richness-2015](https://sedac.ciesin.columbia.edu/data/set/species-global-mammal-
562 richness-2015); the gross domestic dataset is available at
563 <https://datadryad.org/stash/dataset/doi:10.5061/dryad.dk1j0>; the global seismic hazard map are
564 available at <http://gmo.gfz-potsdam.de/>; the global land cover data is available at [http://www.esa-
565 landcover-cci.org/?q=node/197](http://www.esa-
565 landcover-cci.org/?q=node/197); the global soil dataset is available at [http://www.fao.org/soils-
566 portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/](http://www.fao.org/soils-
566 portal/data-hub/soil-maps-and-databases/harmonized-world-soil-database-v12/en/). All datasets are
567 also available upon request from Z. Zeng.

568

569 **Code availability**

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

572

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584

585 **Author contributions statement**

586 Conceptualization: R. X., Z. Z.

587 Methodology: R. X., Z. Z., A. D. Z., L. E. B, J. H., D. S

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591 Project administration: Z. Z.

592 Supervision: Z. Z.

593 Writing – original draft: R. X.

594 Writing – review & editing: All authors contributed interpreting results, and writing and editing the
595 manuscript.

596

597 **Competing interests statement**

598 The authors declare no competing interests.

599

600

601 **Table 1. The theoretical, unused feasible, unused profitable potential and the ratio of the**
602 **national unused profitable potential to the total electricity generation (P/T) in the main**
603 **hydropower countries.** A ratio exceeding one indicates that the countries unused profitable
604 hydropower could fully satisfy total energy demand. Listed are the top 20 countries with unused
605 profitable hydropower potential. The number in the parentheses stands for the percentage of the
606 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 |

607

608 **Figure Legends**

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

614

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

616

617 **Fig. 3. The hydropower development stage of each country and continent.** The green areas
618 represent a country that hydropower development can be continued, the red areas represent the
619 country's developed hydropower exceeds its full profitable potential, the red shaded areas indicate
620 that the country's developed hydropower has exceeded its full feasible potential. The bar chart
621 represents the full feasible, full profitable, and developed hydropower of each continent, and the
622 unit is TWh yr⁻¹.

623

624

625 **References**

- 626 1. Gielen D., Boshell F., Saygin D., *et al.*, The role of renewable energy in the global energy
627 transformation. *Energy Strateg. Rew.* **24**, 38-50 (2019). doi:10.1016/j.esr.2019.01.006
- 628 2. Hart E. K., Jacobson M., The carbon abatement potential of high penetration intermittent
629 renewables. *Energy Environ. Sci.* **5**, 6592-6601 (2012). doi: 10.1039/C2EE03490E
- 630 3. Jacobson M., Krauland A., Coughlin S., *et al.*, Low-cost solutions to global warming, air
631 pollution, and energy insecurity for 145 countries. *Energy Environ. Sci.* (2022). doi:
632 10.1039/D2EE00722C
- 633 4. International Energy Agency (IEA), Global Energy Review 2021. (2021).
634 <https://www.iea.org/reports/global-energy-review-2021>.
- 635 5. Moran E., Lopez M. C., Moore N., *et al.*, Sustainable hydropower in the 21st century. *Proc.*
636 *Natl. Acad. Sci. U.S.A.* **115**, 11891-11898 (2018). doi:10.1073/pnas.1809426115
- 637 6. Latrubesse E., Arima E., Dunne T., *et al.*, Damming the rivers of the Amazon basin. *Nature*
638 **546**, 363-369 (2017). doi:10.1038/nature22333
- 639 7. Maavara T., Chen Q., Meter K., *et al.*, River dam impacts on biogeochemical cycling. *Nat.*
640 *Rev. Earth Environ.* **1**, 103-116 (2020). doi:10.1038/s43017-019-0019-0
- 641 8. Best J., Anthropogenic stresses on the world's big rivers. *Nat. Geosci.* **12**, 7-21 (2019).
642 doi:10.1038/s41561-018-0262-x
- 643 9. Lehner B., Czisch G., Vassolo S., The impact of global change on the hydropower potential of
644 Europe: a model-based analysis. *Energy Policy* **33**, 839-855 (2005).
645 doi:10.1016/j.enpol.2003.10.018
- 646 10. Fekete B., Wissler D., Kroeze C., *et al.*, Millennium Ecosystem Assessment scenario drivers
647 (1970-2050): Climate and hydrological alterations. *Global Biogeochem. Cycles* **24**, GB0A12
648 (2010). doi:10.1029/2009GB003593
- 649 11. Zhou Y., Hejazi M., Smith S., *et al.*, A comprehensive view of global potential for hydro-
650 generated electricity. *Energy Environ. Sci.* **8**, 2622-2633 (2015). doi:10.1039/c5ee00888c
- 651 12. Gernaat D., Bogaart P., Vuuren D., *et al.*, High-resolution assessment of global technical and
652 economic hydropower potential. *Nat. Energy* **2**, 821-828 (2017). doi:10.1038/s41560-017-
653 0006-y
- 654 13. Hoes O. C., Meijer L. J., Ent R., *et al.*, Systematic high-resolution assessment of global
655 hydropower potential. *PLoS One* **2**, e0171844 (2017). doi:10.1371/journal.pone.0171844
- 656 14. Ziv G., Baran E., Nam S., *et al.*, Trading-off fish biodiversity, food security, and hydropower
657 in the Mekong River Basin. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 5609-5614 (2013).
658 doi:10.1073/pnas.1201423109
- 659 15. Pastor A. V., Ludwig F., Biemans H., *et al.* Accounting for environmental flow requirements
660 in global water assessments. *Hydrol. Earth Syst. Sci.* **18**, 5041-5059 (2014). doi:10.5194/hess-
661 18-5041-2014
- 662 16. Jacobson M., Delucchi M., Cameron M., *et al.* Low-cost solution to the grid reliability problem
663 with 100% penetration of intermittent wind, water, and solar for all purposes. *Proc. Natl. Acad.*
664 *Sci. U.S.A.* **112**, 15060-15065 (2015). doi: 10.1073/pnas.1510028112

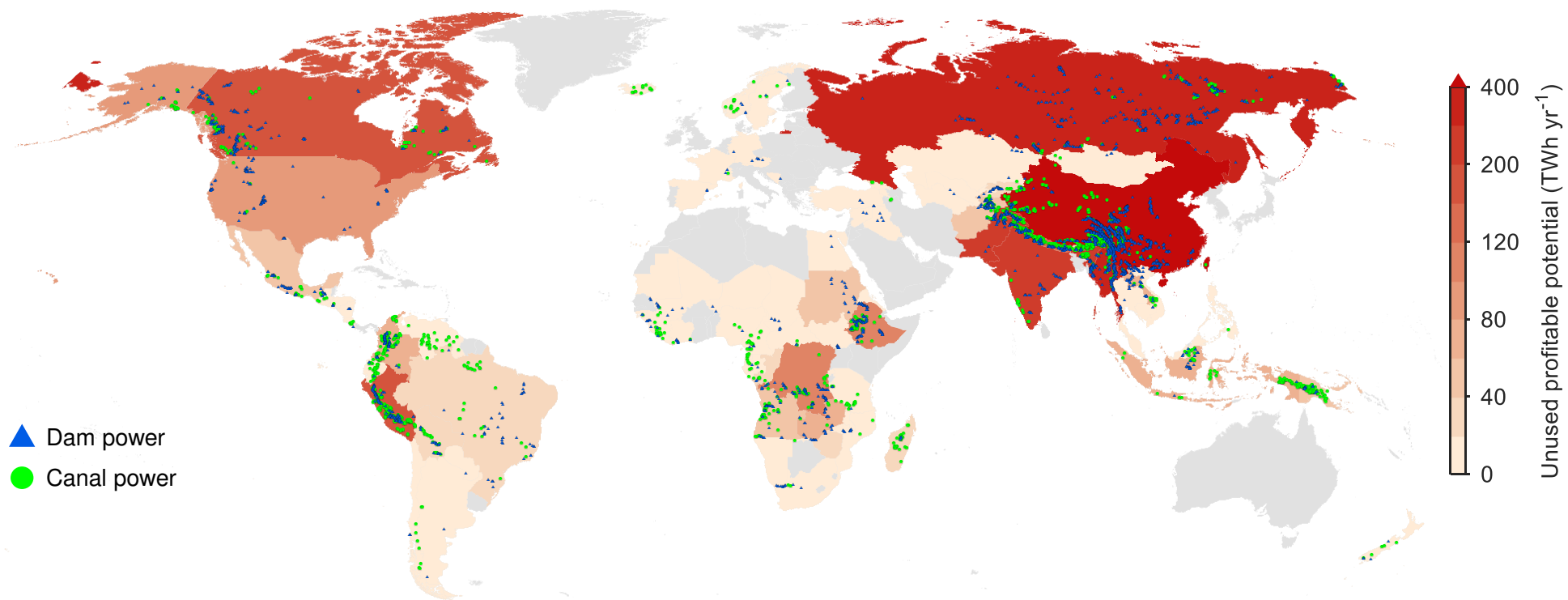
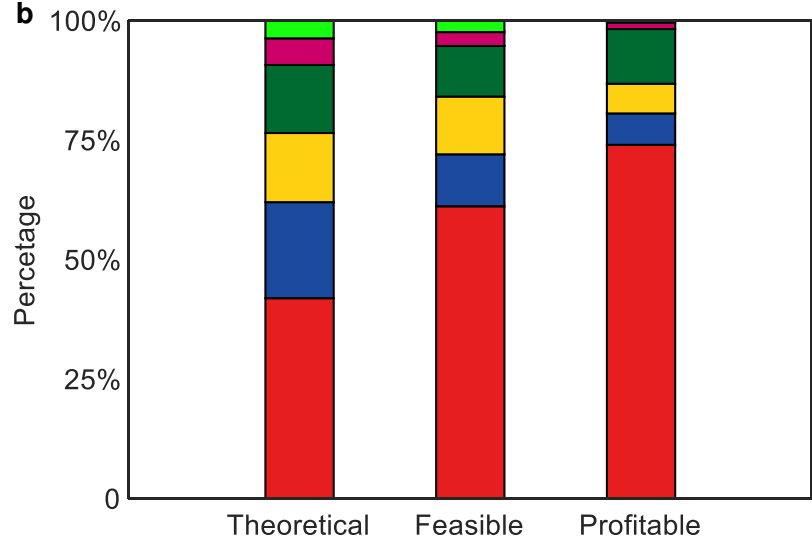
- 665 17. U.S. Department of Energy, An assessment of energy potential at non-powered dams in the
666 United States. (2021). [https://www.energy.gov/eere/water/downloads/assessment-energy-
668 potential-non-powered-dams-united-states](https://www.energy.gov/eere/water/downloads/assessment-energy-
667 potential-non-powered-dams-united-states).
669 18. Kareiva P., Dam choices: Analyses for multiple needs. *Proc. Natl. Acad. Sci. U.S.A.* **109**, 5553-
670 55554 (2012). doi:10.1073/pnas.1203263109
671 19. Poff N., Schmidt J., How dams can go with the flow. *Science* **353**, 1099-1100 (2016).
672 doi:10.1126/science.aah4926
673 20. Poff N., Olden J., Can dams be designed for sustainability?. *Science* **358**, 1252-1253 (2017).
674 doi:10.1126/science.aaq1422
675 21. Lin P., Pan M., Beck H., *et al.*, Global reconstruction of naturalized river flows at 2.94 million
676 reaches. *Water Resour. Res.* **55**, 6499-6516 (2019). doi:10.1029/2019WR025287
677 22. Openstreetmap, 2021. www.openstreetmap.org
678 23. Lehner B., Liermann C. R., Revenga C., *et al.* High-resolution mapping of the world's
679 reservoirs and dams for sustainable river-flow management. *Front. Ecol. Environ.* **9**, 494-502
680 (2011). doi:10.1890/100125
681 24. Mulligan M., Soesbergen A., Sáenz L., GOODD, a global dataset of more than 38,000
682 georeferenced dams. *Sci. Data.* **7**, 31 (2020). doi:10.1038/s41597-020-0362-5
683 25. Wang J., Walter B., Yao F., *et al.* GeoDAR: Georeferenced global dam and reservoir dataset
684 for bridging attributes and geolocations. *Earth Syst. Sci. Data Discuss.* **14**, 1869-1899 (2022).
685 doi:10.5194/essd-2021-58
686 26. IPCC, Climate Change 2022: Impacts, Adaptation, and Vulnerability. (2022).
687 27. Li, D., Lu, X., Walling, D.E. *et al.* High Mountain Asia hydropower systems threatened by
688 climate-driven landscape instability. *Nat. Geosci.* (2022). doi:10.1038/s41561-022-00953-y
689 28. Cáceres A., Jaramillo P., Matthews H. *et al.* Potential hydropower contribution to mitigate
690 climate risk and build resilience in Africa. *Nat. Clim. Change* **12**, 719-727 (2022).
691 doi:10.1038/s41558-022-01413-6
692 29. Bertassoli Jr D. J., Sawakuchi H. O., Araújo K. R. de, *et al.*, How green can Amazon
693 hydropower be? Net carbon emission from the largest hydropower plant in Amazonia. *Sci.*
694 *Adv.* **7**, eabe1470 (2021). doi: 10.1126/sciadv.abe1470
695 30. Millstein D., Wiser R., Mills A. D., *et al.*, Solar and wind grid system value in the United
696 States: The effect of transmission congestion, generation profiles, and curtailment. *Joule* **21**,
697 1749-1775 (2021). doi.org/10.1038/d41586-022-00969-9
698 31. Rehman S., Al-Hadhrami L. M., Alam Md. M., Pumped hydro energy storage system: A
699 technological review. *Renewable Sustainable Energy Rev.* **44**, 586-598 (2015).
700 doi.org/10.1016/j.rser.2014.12.040
701 32. Stocks M., Stocks R., Lu B., *et al.*, Global atlas of closed-loop pumped hydro energy
702 storage. *Joule* **5**, 270-281 (2021). doi: 10.1016/j.joule.2020.11.015
703 33. Hunt J., Byers E., Wada Y., *et al.*, Global resource potential of seasonal pumped hydropower
704 storage for energy and water storage. *Nat. Commun* **11**, 947 (2020). doi:10.1038/s41467-020-
14555-y

- 705 34. Winemiller K. O., McIntyre P. B., Castello L., *et al.* Balancing hydropower and biodiversity
706 in the Amazon, Congo, and Mekong. *Science* **351**, 128-129 (2016).
707 doi:10.1126/science.aac7082
- 708 35. Tamba J., Koffi F., Monkam L., *et al.*, Carbon dioxide emissions from thermal power plants
709 in Cameroon: a case study in Dibamba power development company. *Low Carbon Economy*
710 **4**, 35-40 (2013). doi:10.4236/lce.2013.44A004
- 711 36. Friedlingstein P., O'Sullivan M., Jones M., *et al.* Global Carbon Budget 2020. *Earth Syst. Sci.*
712 *Data* **12**, 3269-3340 (2020). doi:10.5194/essd-12-3269-2020
- 713 37. Hwang S., Cao Y., Xi J., The short-term impact of involuntary migration in China's Three
714 Gorges: a prospective study. *Social Indic. Res.* **101**, pages 73-92 (2011). doi:10.1007/s11205-
715 010-9636-1
- 716 38. Belletti B., Leaniz C. G. de, Jones J., *et al.* More than one million barriers fragment Europe's
717 rivers. *Nature* **588**, 436-441 (2020). doi:10.1038/s41586-020-3005-2
- 718 39. Schiermeier Q., Europe is demolishing its dams to restore ecosystems. *Nature* **557**, 290-291
719 (2018). doi:10.1038/d41586-018-05182-1
- 720 40. Sharma S., Waldman J., Afshari S., Fekete B., Status, trends and significance of American
721 hydropower in the changing energy landscape. *Renewable Sustainable Energy Rev.* **101**, 112-
722 122 (2019). doi:10.1016/j.rser.2018.10.028
- 723 41. Arbuckle E., Binsted M., Davies E., *et al.* Insights for Canadian electricity generation planning
724 from an integrated assessment model: Should we be more cautious about hydropower cost
725 overruns? *Energy Policy* **150**, 112138 (2021). doi:10.1016/j.enpol.2021.112138
- 726 42. Nazareno A., Lovejoy T., Giant dam threatens Brazilian rainforest. *Nature* **478**, 37 (2011).
727 doi:10.1038/478037b
- 728 43. Pritchard H., Asia's shrinking glaciers protect large populations from drought stress. *Nature*
729 **569**, 649-654 (2019). doi:10.1038/s41586-019-1240-1
- 730 44. Ran L., Lu X. X.. Cooperation is key to Asian hydropower. *Nature* **473**, 452 (2011).
731 doi:10.1038/473452c
- 732 45. Hugonnet R., McNabb R., Berthier E., Accelerated global glacier mass loss in the early twenty-
733 first century. *Nature* **592**, 726-731 (2021). doi:10.1038/s41586-021-03436-z
- 734 46. Farinotti D., Pistocchi A., Huss M., From dwindling ice to headwater lakes: could dams replace
735 glaciers in the European Alps? *Environ. Res. Lett.* **11**, 054022 (2016). doi:10.1088/1748-
736 9326/11/5/054022
- 737 47. Shukla T., Sen I., Preparing for floods on the Third Pole. *Science* **372**, 232-234 (2021).
738 doi:10.1126/science.abh3558
- 739 48. Jacobson M., Delucchi M., Bauer Z., *et al.* 100% Clean and Renewable Wind, Water, and
740 Sunlight All-Sector Energy Roadmaps for 139 Countries of the World. *Joule* **1**, 15-17 (2017).
741 doi:10.1016/j.joule.2017.07.005
- 742 49. Yamazaki D., Ikeshima D., Tawatari R., *et al.* A high-accuracy map of global terrain
743 elevations. *Geophys. Res. Lett.* **44**, 5844-5853 (2017). doi:10.1002/2017GL072874
- 744 50. Yamazaki D., Ikeshima D., Sosa J., MERIT Hydro: A high-resolution global hydrography map

- 745 based on latest topography dataset. *Water Resour. Res.* **55**, 5053-5073 (2019).
746 doi:10.1029/2019WR02487
- 747 51. Beck H., Wood E., Pan M., *et al.* MSWEP V2 Global 3-Hourly 0.1° Precipitation:
748 Methodology and Quantitative Assessment. *Bull. Am. Meteorol. Soc.* **100**, 473-500 (2019).
749 doi: 10.1175/BAMS-D-17-0138.1
- 750 52. UNEP-WCMC, The World Database on Protected Areas (WDPA) (2015)
- 751 53. International Union for Conservation of Nature (IUCN) and UNEP-WCMC. KML layer of
752 natural and mixed world heritage sites as recorded in the World Database on Protected Areas
753 (WDPA). http://www.iucn.org/sites/dev/files/import/downloads/natural_and_mixed_world_heritage_sites_2014.kmz (2013)
754
- 755 54. Lehner B., Döll P., Development and validation of a global database of lakes, reservoirs and
756 wetlands. *J. Hydrol.* **296**, 1-22 (2004). doi:10.1016/j.jhydrol.2004.03.028
- 757 55. Turubanova S., Potapov P., Tyukavina A., Ongoing primary forest loss in Brazil, Democratic
758 Republic of the Congo, and Indonesia. *Environ. Res. Lett.* **13**, 074028 (2018).
759 doi:10.1088/1748-9326/aacdlc
- 760 56. Xu J., Morris P., Liu J., Holden J., PEATMAP: Refining estimates of global peatland
761 distribution based on a meta-analysis. *CATENA* **160**, 134-140 (2018).
762 doi:10.1016/j.catena.2017.09.010
- 763 57. OAK RIDGE National Laboratory, LandScan Global 2019. <https://landscan.ornl.gov/> (2020)
- 764 58. Fischer G., Nachtergaele F., Prieler S., *et al.* Global Agro-ecological Zones Assessment for
765 Agriculture. (GAEZ 2008, <https://core.ac.uk/download/pdf/52948018.pdf>)
- 766 59. Shedlock K.M., Giardini D., Grunthal G., Zhang P., The GSHAP Global Seismic Hazard Map.
767 *Seismol. Res. Lett.* **71**, 679-686 (2000). doi: 10.1785/gssrl.71.6.679
- 768 60. Dijkstra E. W., A note on two problems in connexion with graphs. *Numer. Math.* **1**, 269-271
769 (1959). doi:10.1007/BF01386390
- 770 61. Farinotti D., Round V., Huss M., *et al.*, Large hydropower and water-storage potential in future
771 glacier-free basins. *Nature* **575**, 341-344 (2019). doi:10.1038/s41586-019-1740-z
- 772 62. Kummu M., Taka M., Guillaume J., Gridded global datasets for Gross Domestic Product and
773 Human Development Index over 1990-2015. *Sci Data* **5**, 180004 (2018).
774 doi:10.1038/sdata.2018.4
- 775 63. UNEP-WCMC, UK National Ecosystem Assessment (Cambridge, 2011; <http://uknea.unep-wcmc.org/>)
776
- 777 64. United States Department of Agriculture, Land Values 2020 Summary. (2020;
778 https://www.nass.usda.gov/Publications/Todays_Reports/reports/land0820.pdf#:~:text=4%20Land%20Values%202020%20Summary%20%28August%202020%29%20USDA%2C,per%20acre%20for%202020%2C%20no%20change%20from%202019.)
779
- 780 65. Spawn S., Sullivan C., Lark T., Gibbs H., Harmonized global maps of above and belowground
781 biomass carbon density in the year 2010. *Sci Data* **7**, 112 (2020). doi:10.1038/s41597-020-
782 0444-4
783
- 784 66. International Union for Conservation of Nature - IUCN, and Center for International Earth

785 Science Information Network - CIESIN - Columbia University.2015.Gridded Species
786 Distribution: Global Amphibian Richness Grids, 2015 Release. Palisades, NY: NASA
787 Socioeconomic Data and Applications Center (SEDAC). doi:10.7927/H4RR1W66
788 67. Federal Emergency Management Agency, National Inventory of Dams (2022).
789 [https://www.fema.gov/emergency-managers/risk-management/dam-safety/national-
791 inventory-dams](https://www.fema.gov/emergency-managers/risk-management/dam-safety/national-
790 inventory-dams).
792 68. Robert J. Hijmans, Database of Global Administrative Areas. (2022). <https://gadm.org/>.
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