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In-stream turbines for rethinking hydropower development in the Amazon basin

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Given growing energy demands and continued interest in hydropower development, it is important that we rethink hydropower to avoid detrimental socioenvironmental consequences of large dams planned in regions such as the Amazon River basin. Here, we show that ~63% of total energy planned to be generated from conventional hydropower in the Brazilian Amazon could be harnessed using in-stream turbines that use kinetic energy of water without requiring storage. At five of the nine selected planned dam sites, the entirety of energy from planned hydropower could be generated using in-stream turbines by using only a fraction of the river stretch that large dams would affect. We find the cost (US$ kWh^{-1}) for in-stream turbines to be ~50% of the conventional hydropower cost. Our results have important implications for sustainable hydropower development in the Amazon and worldwide through transition to power generation methods that meet energy needs while minimizing the negative socioenvironment impacts.

Hydropower is by far the largest source of renewable energy and accounts for ~50% (ref. [1]) and ~65% (ref. [2]) of global renewable energy and electricity production, respectively. Given that hydropower is a relatively clean source of energy and there is a predicted upsurge in its contribution to the global energy mix[3,4], hydropower is expected to remain a promising source of energy for the foreseeable future[3,5–7]. However, there have been increasing concerns as to whether the energy benefits can outweigh the detrimental socioenvironmental consequences of storage reservoir-based hydropower projects[3]. Hydropower has often been developed with a primary focus on energy generation, neglecting the social and environmental costs[8]. Because the economic benefits are often overstated and the adverse effects underestimated during the design and implementation processes, conventional hydropower technologies have been surrounded by controversies related to their long-term implications on environmental systems and social well-being[5,8,9]. As the recognition of these effects has grown, dam removal has been on the upward trend in recent years[10] in regions with aging dams (such as the United States and Europe); concomitantly, hundreds of large and small dams are being built or planned in other global regions including the Amazon, Congo and Mekong river basins[5].

Given these ongoing and planned hydropower developments, losses in biodiversity[3,5,11–13] and fragmentation of river connectivity[14,15] are inevitable when conventional hydropower technology is used. Yet, dams continue to be built in exceptionally biodiverse sites (for example, in the Amazon basin), setting records in biodiversity losses[5]. Storage-based hydropower projects are known to alter basin hydrology with adverse and often 'characteristically irreversible'[12] consequences on a range of environmental, agricultural and socioeconomic systems. Impediments to fish migration[8], alterations in freshwater discharge to oceans[16], reductions in sediment movement[12] and nutrient transport[17], river fragmentation[15], disruption of flood pulse dynamics[6] and delta erosion[18] are some of the direct and observed consequences of large dams in many global river basins. Further, the increase in greenhouse gas emissions from reservoirs[9] and deforestation can be exacerbated by storage-based dams, especially in tropical regions such as the Amazon basin. There is evidence that even the run-of-the-river hydropower plants cause profound changes in riverine habitat[19] although the impacts are less severe compared to that of large, storage-based projects[20].

Therefore, it is important to rethink hydropower development along with its planning and decision-making process to avoid potential negative impacts of large dams. In storage-based hydropower systems, the flowing water is impounded to accumulate potential energy and maximize power extraction in one location, which is then converted to kinetic energy. A more sustainable solution for generating power may be the direct use of the kinetic nature of streams and river channels, hence avoiding water impoundment. Such kinetic energy can be harnessed by in-stream turbines that operate on fundamentally similar principles to that of wind turbines[21] but under water. This leads to the question: is it feasible to use in-stream turbines to harness a large portion of the power that is expected to be generated by building large dams?

A large body of literature exists on the assessment of hydropower potential[4,22–24], however, the aim of these studies has been to assess the potential that can be harnessed by using conventional technologies. In-stream turbine technology has been evolving and gaining traction in recent years[21,25–32]; however, rather limited research has been conducted to assess the potential and feasibility of using this technology over large regions such as the Amazon basin. The focus of most of the existing in-stream turbine-related studies has been on the design of turbine arrays in tidal channels[21,26–28]; studies with a focus on in-stream turbines in riverine environments are scarce, with some exceptions[29,33]. Studies investigating kinetic energy extractions from tidal channels have shown that the safe extraction capacities for kinetic energy flux, without substantially altering the natural flow dynamics[21,30–32], can be 10–20% of the total available energy. Although, these studies represent tidal channels, it is reasonable to use a similar approach to estimate energy extraction in riverine environments with wide stream channels[29] such as those in the Amazon.

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Here, we estimate the technical in-stream potential (TIP) in the Amazon River basin which is a measure of the kinetic energy potential that can be extracted by using in-stream turbines in the rivers (Methods). Our TIP assessment follows an approach that optimizes annual energy benefits by using flow duration curves (Supplementary Figs. 1 and 2) derived from a high-resolution (1 arcmin; ~2 km), physically based continental-scale hydrological model, the LEAF-Hydro-Flood (LHF)[34,35]. We consider multiple rows of in-stream turbines with constant spacing distinguished under two scenarios: 40× and 10× the turbine diameter (hereafter 40D and 10D, respectively; Methods). The 40D scenario is used as a basin-wide sustainability criterion to analyse the in-stream potential in each grid cell, whereas the 10D scenario is used for site-specific analysis at planned dam locations. We also estimate the potential energy-based hydropower potential of the Amazon with an upper threshold of Q_{30}, the flow that is equalled or exceeded 30% of the time in a year, hereafter referred to as integrated gross hydropower potential with Q_{30} ($IGHP_{30}$). Further, we evaluate the suitability for in-stream power generation within the Brazilian Amazon using three metrics and systematically explore each site with respect to the energy demand of the region, protected areas in the vicinity and availability of TIP (Methods). Each suitability criterion is expressed in terms of an index—the energy demand index (EDI), protected area index (PAI) and in-stream potential index (IPI), respectively, calculated for each municipality within the Brazilian Amazon. Finally, in-stream turbines are placed in an economical perspective by comparing their energy costs with storage-based dams at nine planned dam sites in the Amazonian lowlands (Supplementary Fig. 3) to elucidate the additional merits of rethinking hydropower design for future development.

Integrated gross hydropower potential

The total $IGHP_{30}$ for the entire Amazon basin is estimated at 3,793 TWh yr^{-1} (Fig. 1a,b). Characterized both by high flows and steep slopes, the Solimoes possesses the highest $IGHP_{30}$ (942 TWh yr^{-1}) among the eight sub-basins (Supplementary Fig. 3), followed by the Madeira (433 TWh yr^{-1}) and Negro (415 TWh yr^{-1}) river basins (Fig. 1b). About 23% of the gross potential is contained within the Andean Amazon due to the combined effect of high annual streamflow and rugged topography that provides high head drop. Our $IGHP_{30}$ estimate for the entire Amazon aligns closely with estimates provided in previous studies[4,22,24] (Supplementary Table 1). However, differences are evident at the sub-basin level which could be attributed to the differences in model input and model grid resolution. Previous studies used either low resolution (1° × 1°; ~100 km) model grid cells[22] or streamflow estimates derived by downscaling coarse resolution global hydrological model output[24]. Our approach, by comparison, directly uses high-resolution streamflow that has been extensively validated across the entire basin[34,35], which adds confidence to our estimates (Methods). Further, the use of river bottom elevations derived from a high-resolution digital elevation model (DEM) in this study (Methods) could have also added to the discrepancy with previous estimates[22,24]. A comparison of IGHP estimates, calculated using different exceedance flows, is presented in Supplementary Fig. 4. These comparisons provide confidence for our use of model simulations in estimating hydropower potential in the Amazon.

Technical in-stream potential

We find high potential for in-stream power generation across the Amazon basin (Fig. 1c). As expected, high TIP is seen in the Amazonian lowlands, such as the Solimoes river floodplains (Fig. 1c, box 3) and the Amazon main stem, regions characterized by high flows and wide channels. Notwithstanding the high concentration of $IGHP_{30}$ in the Andes, TIP estimates suggest higher potential for using in-stream turbines in the Amazonian lowlands compared to the Andean river stretches (Fig. 1c, box 4). Narrow channels through rugged topography and shallow water depths are the primary reasons for low TIP in most of the Andean river stretches. Yet, for the Andean river stretches with sufficient water depths (>2 m; Methods), in-stream turbines may prove useful with site-specific optimization of the design factors, such as the inter-row turbine spacing and blockage ratio.

Evidently, most of the locations with high TIP in the Amazonian lowlands overlap with the planned dam sites with high generation capacity (Fig. 1c, boxes 1 and 2). At five of the nine planned dam sites considered in this study (Supplementary Fig. 3), in-stream turbines could be used to exploit the entirety of planned generation capacity while using only a fraction of the river stretch (Supplementary Table 2) under the 10D scenario. For example, high TIP (671 MW; Fig. 1c, box 1) is found in the ~15-km river stretch in the vicinity of the Bem-Querer dam (650 MW), the largest dam planned to be built in the Amazon by 2029[36]. Similarly, at other planned dam sites, such as Jatoba and Prainha (Fig. 1c, box 2), in-stream turbines could be used to harness the entire planned dam capacity from ~32- and ~47-km river stretches, respectively. Overall, our estimate suggests that ~63% (~9,791 MW) of the total planned dam capacity in the Brazilian Amazon could be harnessed in the region of the planned dams (>30 MW) by using in-stream turbines under the 10D scenario (Fig. 1d and Supplementary Fig. 5). This suggests that in-stream turbines are viable alternatives to conventional dam projects in many locations in the Amazon.

Suitability of in-stream turbines

Our results suggest that the Madeira and Tapajos—the sub-basins of the Amazon likely to be threatened the most by a number of existing and planned hydropower dams[12]—are the most suitable regions for deploying in-stream turbines instead of large dams. Regions with high in-stream suitability (for example, municipalities including Itaituba and Jacareacanga; Fig. 2 and Supplementary Fig. 6), overlap with the locations of many of the planned dams such as Jatoba, which are included in Brazil's 10-yr energy expansion plan[36]. These municipalities along with others in the middle reaches of the Tapajos and Madeira rivers are characterized by high suitability, making this region particularly suitable for in-stream turbines. Further, municipalities situated in the Negro river basin also indicate high suitability for in-stream turbines, especially around the Bem-Querer dam which is planned to be constructed in the coming decade[36].

Further, high suitability can be seen in the Brazilian municipalities that house some of the major operational hydropower projects (Fig. 2), which adds confidence to our finding about the possibility of using in-stream turbines as an alternative to large dams. For example, the high IPI is observed around Porto Velho—municipality where Santo Antonio (3,568 MW) and Jirau (3,750 MW) dams are located. Similarly, high suitability can be seen in the municipalities such as Baiao, Breu, Branco, Moju, Pacaja and Tailandia (Fig. 2) that are in the vicinity of the largest dam in the Tocantins basin (Tucurui I and II; 8,370 MW).

Northern and southern stretches of the Brazilian Amazon also exhibit high suitability because of high PAI and IPI (Methods); these areas include major cities such as Ji-Paraná and Sinop in the upstream reaches of the Madeira and Tapajos rivers, respectively (Fig. 2 and Supplementary Fig. 6). In most of the central and eastern regions of the Brazilian Amazon, the suitability is dominated by IPI (Fig. 2 and Supplementary Fig. 6) owing to the large areas under protection (low PAI) and sparse population (low EDI).

Cost comparison between conventional and in-stream hydropower

Levelized cost of electricity (LCOE) estimates for in-stream turbines (3.8–4.4 cents kWh^{-1}) are found to be 46–54% of the average reported cost of energy from existing hydropower dams

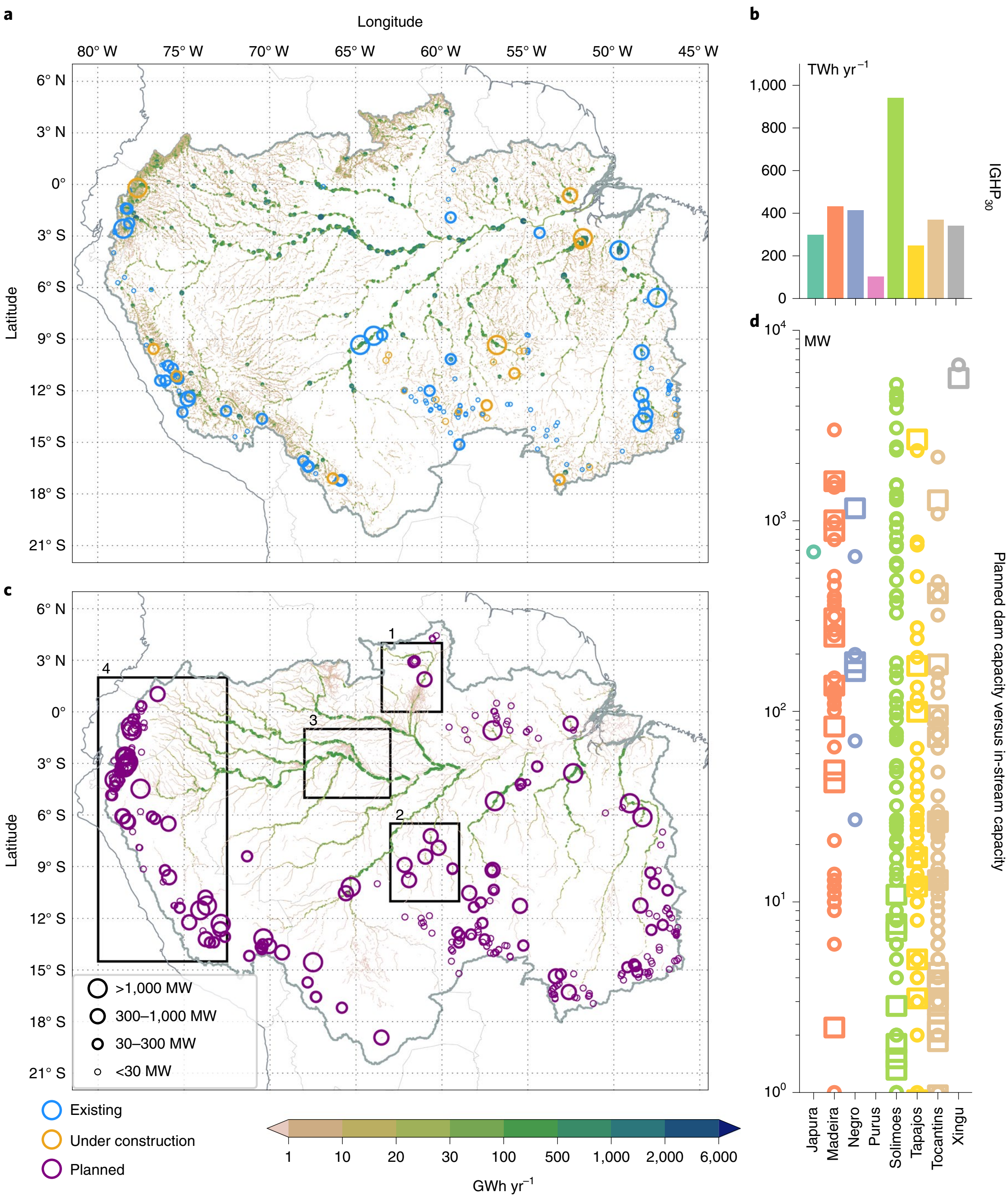

Fig. 1 | Hydropower potential in the Amazon. a,**b**, IGHP$_{30}$ in the Amazon river basin (**a**) and its sub-basin level distribution (**b**). **c**, TIP in the Amazon under the 40D scenario. Boxes 1–4 are explained in the text. **d**, Comparison of the power generation capacities and TIP under the 10D scenario at the planned dam sites in the Amazonian sub-basins. Squares and circles in **d** indicate in-stream capacities and planned dam capacities, respectively. The IGHP$_{30}$ for small sub-basins located in the northeast of the Amazon are not shown in **b**. Sub-basin boundaries are shown in Supplementary Fig. 3.

(~8.2 cents kWh^{-1}) across Brazil (Fig. 3) as reported in the Agência Nacional de Energia Elétrica (ANEEL) database (http://www.aneel.gov.br/). On a sub-basin level, the average reported cost for existing dams (>30 MW) varies from 11.6 cents kWh^{-1} in the Madeira to 7.4 cents kWh^{-1} in the Tocantins. Although, the existing mega-dams (for example, Jirau and Santo Antonio) in the Madeira basin are run-of-the-river plants, their actual cost is high, with an average of 8.1 cents kWh^{-1}.

The estimated costs for the nine planned dams (Fig. 3, brown polar bars) in the Brazilian Amazon are substantially lower than the reported cost of their predecessors (Fig. 3, orange dots). This implies that for a proper interpretation of the costs for hydropower projects, it is essential to consider the actual costs of existing dams which may already account for the highly uncertain costs caused by social and environmental changes, construction difficulties and management irregularities or, to a certain extent, the delays in political decision-making. Surprisingly, and as discussed above, the average estimated cost for planned dams in the Brazilian Amazon is found to be much lower (6.2 cents kWh^{-1}) than the average reported cost of existing dams (8.2 cents kWh^{-1}; Fig. 3). Costs estimated for

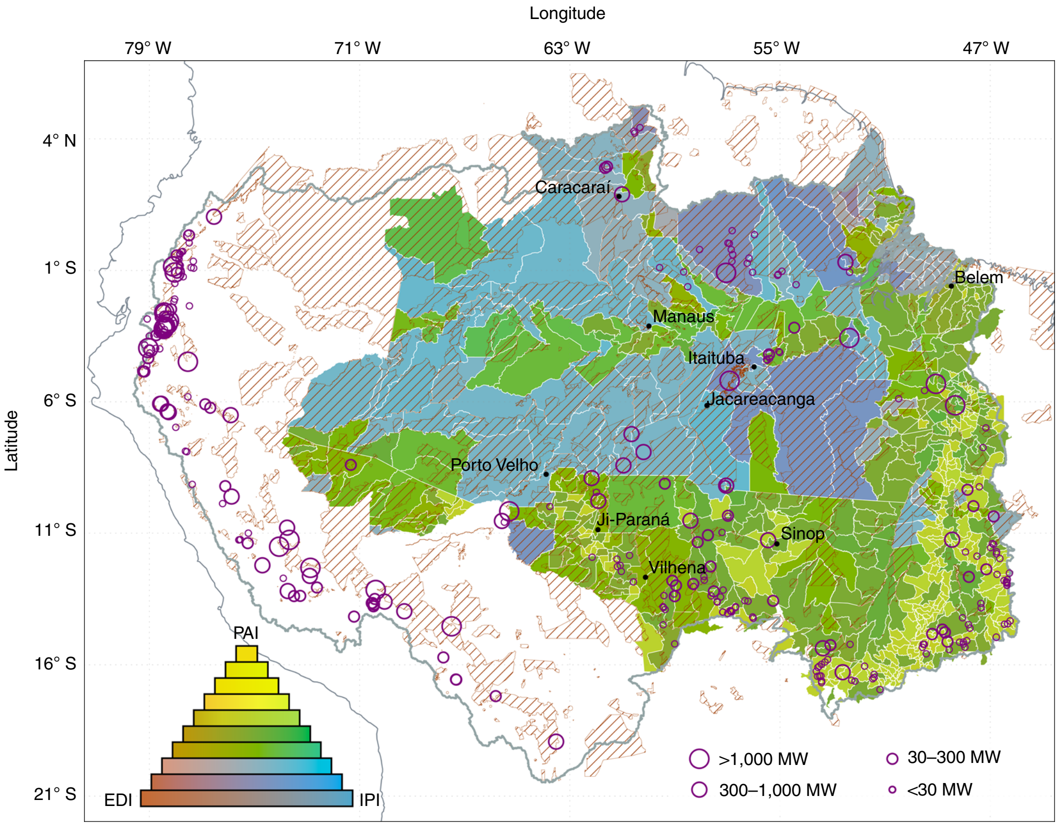

Fig. 2 | Suitability indices for in-stream turbines in the Brazilian Amazon. Suitability of in-stream turbines is depicted in terms of three indices: PAI, protected area index; IPI, in-stream potential index; and EDI, energy demand index, at a municipality level in the Brazilian Amazon. Blue shade indicates domination of IPI, whereas yellow and red shades indicate domination of PAI and EDI, respectively. Brown hatches indicate the protected areas defined by WDPA. Purple circles mark the planned dam sites.

the existing dams account for only ~75% of their average reported costs in the ANEEL database, with some existing dam sites going as low as ~25%. Detailed cost breakdowns for hydropower dams are provided in Supplementary Fig. 7.

On the contrary, the cost of in-stream turbines (average 4.1 cents kWh^{-1}) is largely the same for all locations as the cost equation is only a function of generated power and is subject to less uncertainties because the environmental and social costs, including those caused by water impoundment, sediment accumulation, resettlement of populations and reduced fish productivity, are bound to be minimal compared to storage-based hydropower projects.

Discussion

Our findings suggest that there is high potential for using in-stream turbines in the Amazon as an alternative to the planned storage-based hydropower projects. Site-specific analysis indicates that at five of the nine planned dam sites in the Brazilian Amazon, in-stream turbines could be used to harness equivalent amounts of energy to be produced from storage-based dams, with substantial reduction in environmental and social impacts. High potential for using in-stream power generation is found also at the remaining four planned dam sites. These findings have important implications for sustainable hydropower development in the Amazon basin by reducing the environmental, social and economical losses associated with large-scale, storage-based[3,5,8,9,12] and even run-of-the-river[19] hydropower projects that are planned across the basin. With the assumed generic turbine array arrangement, we find that the potential for in-stream turbines is high in the Amazonian lowlands; site-specific optimization of turbine array arrangement could lead to increased suitability of in-stream turbines at the Andean dam sites, which could help maintain the Andes–Amazon connectivity[14,15].

Our power potential estimates are based on the best datasets currently available, combined with a state-of-the-art hydrological model. We expect that as specific projects in the Amazonian sub-basins are developed, enhanced site-specific analyses would enable optimization of in-stream turbine array design with respect to local site conditions. It is expected that the power potential would differ from that presented in this study because our approach leads to rather conservative estimates (Methods). Combining our results with relevant regional information (for example, fishing hotspots, navigational routes and areas of cultural importance) could help identify and prioritize locations for in-stream hydropower development and further examine their trade-offs with ecological factors including river bottom habitats and sediment transport.

Actual costs of conventional hydropower far exceed the predicted costs, with as high as a fourfold increment in some dam sites (~96% higher globally[37]), which probably comes from the underestimation of environmental and social costs[37] owing to inaccurate assessment of inundated areas and displaced population[19]. Additional costs from construction difficulties due to geological complexities[38] and project delays[37,39] also often occur in mega-dam projects. Furthermore, with ongoing deforestation[3] and potential reduction in power generation due to climate change and variability[3], the costs of conventional hydropower may increase in the future. For example, the Belo Monte dam in the Xingu River is expected to produce only 4.46 GW (ref. [3]) of the 11.23 GW installed capacity in many months of each year due to low water levels. These inevitable costs combined with the often-neglected costs that incur from delays in juridical contestation

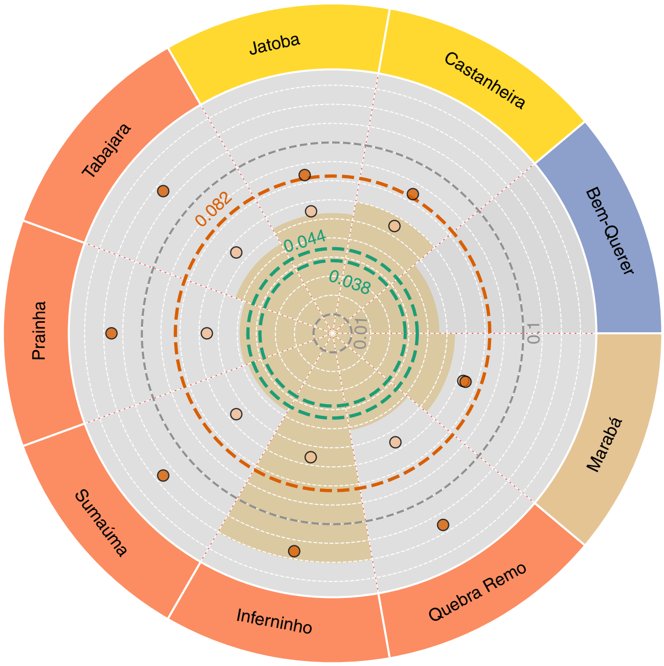

Fig. 3 | Comparison of costs for conventional hydropower and in-stream turbines. Results shown are for the nine planned dams in the Brazilian Amazon (Supplementary Fig. 3). Brown polar bars indicate the predicted storage-based hydropower dam cost. Green dashed lines indicate the range of estimated cost among three different types of in-stream turbines at the planned dam locations. Light and dark orange dots, respectively, show the average estimated cost and the average reported cost (obtained from ANEEL database) for existing dams (>30 MW) in the corresponding sub-basin (colour coding is the same as in Fig. 1; the sub-basins are shown in Supplementary Fig. 3). Orange dashed line shows the average cost of all existing dams (>30 MW) in Brazil. All costs are expressed in terms of LCOE in US$ kWh^{-1}. Note that no dams are currently operational in the Negro River basin.

and management irregularities[3] reduce the benefit-to-cost ratio of conventional hydropower well below one.

On the contrary, in-stream turbines can provide a relatively cost-efficient and benign energy production system compared to conventional hydropower. In-stream turbines have already been implemented globally, most of them being individual turbines in rural areas with the exception of the installations in the Alaskan rivers[40]. Since these installations are relatively new, many aspects of their operation, reliability and life span in varying geographic and hydrologic conditions are yet to be fully tested. However, the possible impacts of a large-scale implementation of in-stream turbines can be assessed on the basis of the results of their marine counterparts—the tidal turbines. Deploying large turbine arrays in river channels may have undesirable consequences on the riverine environment. Reduced navigational capabilities during extreme droughts, alterations in fishing routine[41] and increased water levels downstream could be some of the potential effects; however, the adverse socioenvironmental impacts are expected to be relatively less than those of large dams. Further, the cost estimates provided in this study assume that each in-stream turbine in an array generates energy close to the rated power. Although this can be achieved by careful site-specific turbine array design and placement[28], variations in the total power generation can be expected due to the fluctuations in river velocities, causing a deviation from the predicted costs of in-stream turbines. Further, in-stream turbine projects may also suffer from cost overruns—like large dam projects—owing to project delays but the overruns caused by underestimated environmental and social costs, geological complexities and decommissioning would be lower than those for large hydropower dams.

Nevertheless, in-stream turbine development in the Amazon aligns well with the needed efforts to preserve the Amazonian forests[42,43] and their critical role on global terrestrial water balance and climate dynamics[44], along with the preservation of unique Amazonian habitats[12]. Indeed, the benefits of developing in-stream turbines instead of large dams extend well beyond the reduction of environmental impacts caused by dams; other benefits include elimination of forced relocation of human populations along with economic, cultural and social costs that dams impose. While, for the time being, conventional hydropower dam projects in the Amazon basin are on hold or being cancelled owing to injunctions requested by Indigenous peoples and local communities, the energy sector has not entirely renounced dam building in the region, making it increasingly important to examine alternatives to dams for continued use of renewable energy resources. However, replacing dams with in-stream turbines alone is not expected to entirely transform the hydropower sector. A transition from the single-minded focus on energy production, promoting integrated water management through incorporation of local community concerns and a greater transparency in the decision process is essential. Strategic planning which follows a nexus approach that integrates food, energy and water systems, and uses innovative analytical methods that account for larger implications which go beyond political boundaries should be considered to increase the overall credibility of hydropower.

In summary, this study provides a solid foundation to rethink hydropower dams and provides insights on new and important alternatives for sustainable hydropower development. Over the long run, this assessment could prove beneficial in investigating the future of hydropower in the Amazon and other regions worldwide (for example, the Mekong and Congo river basins) where a boom in construction of mega-scale hydropower dams is underway[7]. The flexibility of our framework also provides wide-ranging applications for future studies related to the development of hydrokinetic power generation globally.

Methods

The model, data and methods used in this study are described in the following.

Model and data. High-resolution (1 arcmin or ~2-km grids) climatological mean daily streamflow is simulated by the LHF model[34,45], a physically based continental-scale land hydrology model that resolves various land surface hydrologic and groundwater processes on a full physical basis. The backwater effect that is prominent in parts of the Amazon basin is also simulated in LHF. All simulation settings are identical to that used in our recent study[34]. The annual flow duration curves (Supplementary Fig. 1) are generated from the 36-yr (1980–2015) average streamflow simulated by LHF. LHF model has been used and validated over the Amazon in our previous studies[34,35] using a comprehensive set of ground- and satellite-based observations. For completeness, here we briefly revisit the validation of simulated streamflow and terrestrial water storage (Supplementary Fig. 8). Streamflow estimates used in this study are without existing dam operations and could contain some uncertainties in the vicinity of existing dams because dams can alter flow patterns and velocity[46]. However, the impact of existing dams on streamflow in most of the Amazon is known to be minimal because the degree of current regulation is relatively small compared to the natural seasonal variations[47]. Following our previous studies[34,35,48], river parameters (for example, flow direction and river length within a grid cell) are obtained through up-scaling[49] of the 15-arcs flow direction data from HydroSHEDS[50]. The empirical relationship based on the drainage area is used to determine the channel width, following Coe et al.[51].

Information on the protected areas in the Amazon is obtained from the world database of protected area (WDPA; https://www.protectedplanet.net). Brazilian census data come from the Instituto Brasileiro de Geografia e Estatística (IBGE; https://www.ibge.gov.br), which are used to calculate the future energy demand of municipalities and derive the number of households reported to have no access to electricity.

Dam locations are compiled from four sources: (1) Global Georeferenced Database of Dams (GOOD)[52], (2) Future Hydropower Reservoirs and Dams (FHReD)[53], (3) ANEEL and (4) State of the World's Rivers dam database (www.internationalrivers.org). Detailed information about the selected dams (such as dam height, reservoir capacity and power generation capacity) is obtained from the ANEEL dam database.

Integrated gross hydropower potential. IGHP at every grid cell is calculated by using the widely used potential energy-based formulation[4,22–24]:

$$E_{\mathrm{annual}} = \sum_{i=1}^{365} (\rho g Q H) \times t \begin{cases} Q = Q_{\mathrm{D}} \text{ if } Q_i > Q_{\mathrm{D}} \\ Q = Q_i \ \text{ if } Q_i \leq Q_{\mathrm{D}} \end{cases}$$

where E_{annual} is the annual potential energy in watt-hour ($\mathrm{M\,L^2\,T^{-3}}$), ρ is the density of water ($\mathrm{M\,L^{-3}}$), g is the gravitational acceleration ($\mathrm{L\,T^{-2}}$), Q_i ($\mathrm{L^3\,T^{-1}}$) is the daily discharge in the grid cell, Q_{D} is the design discharge, H (L) is the head difference and t (T) is the operational hours per day; dimensions are mass (M), length (L) and temperature (T). Head difference is estimated as the difference in riverbed elevation between the grid cell considered and its downstream grid cell. Riverbed elevation at every model grid cell is estimated by averaging the elevation of the river grid cells from a finer resolution (3 arcs or ~90 m) DEM from HydroSHEDS[50]. Such averaging provides a more realistic head gradient along the river compared to the head difference obtained as the difference of mean grid cell elevation between two consecutive grid cells. While there exists no common consensus regarding the streamflow threshold in the past literature, we use the flow with 30% exceedance probability (Q_{30}; which is the flow that is equalled or exceeded 30% of the time in a year) estimated from the flow duration curve for each grid cell, which is commonly used in hydropower design[23]. To maintain consistency with previous studies[22–24], we also estimate annual potential energy using the annual mean flow, instead of the Q_{30} (Supplementary Fig. 2). Furthermore, we use a pragmatic approach—the annual integration approach—in view of the seasonal streamflow variations, by first calculating the daily hydropower potential with a Q_{30} threshold and then integrating the potential to estimate IGHP_{30}, hence avoiding the overestimation of potential due to the use of mean annual streamflow (Supplementary Fig. 2).

Technical in-stream production. TIP is calculated at each grid cell using the kinetic energy formulation:

$$\mathrm{TIP}_{\mathrm{annual}} = \sum_{i=1}^{365} \eta C_{\mathrm{p}} B \times \left(\frac{1}{2}\rho W H_{90} V_i^3\right) \times t$$

where, η is turbine efficiency (90%; ref. [4]), C_{p} is power coefficient, B is blockage ratio, ρ ($\mathrm{M\,L^{-3}}$) is density of water, W (L) is river channel width, H_{90} (L) is flow depth which equals or exceeds 90% of the time, V ($\mathrm{L\,T^{-1}}$) is flow velocity for each day of the year simulated by LHF[34] and t (T) is operational hours per day. For blockage ratio, a constant value of 0.284 is assumed, following previous literature[28]. The power coefficient is assumed to be 0.35, which is an average value commonly used to estimate power conversion[54]. Assumed blockage ratio and power coefficient together result in an extraction of ~10% of the total available kinetic energy to minimize the impact on downstream flow characteristics, a limit commonly referred to as the 'safe extraction limit'[21,25,30]. The value H_{90} is estimated from the 36-yr averaged daily flow depths simulated by LHF. To account for the high seasonality of flow in the Amazonian sub-basins (for example, Tocantins), in-stream turbines are considered only in a part of the river cross-section corresponding to the area with respect to H_{90}. To remain conservative and for cost-effective power generation, river stretches with water depth <2 m and velocity $<0.5\,\mathrm{m\,s^{-1}}$, corresponding to Q_{90} (the flow equalled or exceeded 90% of the time during a year) are excluded from the TIP analysis. Moreover, the river stretches within protected areas are entirely excluded.

In-stream power generation capacity at the planned dam sites is estimated as the sum of TIP in the river grid cells upstream of the dam site along the river, with an upper threshold of the river stretch that would be affected if the dam is constructed. River stretch affected by planned dams is estimated considering inundation areas, traced by upstream tracking of the reservoir on a high-resolution (~90 m) DEM using dam height[55]. For planned dam sites with no dam height specified, we assume the affected river stretch to be equal to either the distance to an upstream dam or 50 km, whichever is lower. The 50-km threshold is selected to remain conservative in estimating the cost of planned dams. The length of reservoirs created by existing dams such as Jirau and Santo Antonio in the Madeira river basin is >100 km, even though both are considered run-of-the-river projects.

We adopt the physical properties of in-stream turbines, such as the diameter (1 m) and the minimum flow depth required (2 m), on the basis of the specifications of Smart Hydro Power's Smart Mono Float turbine and Smart Free Stream turbine (https://www.smart-hydro.de/). The Smart Hydro Power turbines are selected because these turbines are commercially available and have been successfully implemented and tested in river stretches around the world. Further, the structure of Smart Hydro Power turbines allows them to be installed on the riverbed, avoiding potential interferences with river navigation, prominent in the Amazonian rivers. Previous studies have shown that the flow recovery length following an upstream turbine array varies from 3× to 40× the turbine diameter (D), depending on the array arrangement (straight and staggered) and turbulence model[27,28]. We take a conservative approach by considering a minimum inter-row spacing of arrays as 10× the turbine diameter (10D; ref. [29]) at planned dam sites.

For a basin-wide analysis, we use an inter-row spacing of 40× the turbine diameter (40D; ref. [27]) as a sustainability criterion, which represents a case with high likelihood that the velocity becomes uniform before reaching the next turbine row. The 10D scenario, which still has a relatively high likelihood that the flow velocity becomes uniform before the next downstream array[27,28], is considered strictly for site-specific analysis, such as the TIP comparison with planned dam capacities. Here, for the estimation of TIP, we assume complete velocity recovery to natural condition downstream of a turbine row. Note that our approach does not consider the influence of lateral turbine spacing on flow velocity, which has been known to benefit the total output of the turbine array from the 'duct effect' caused by the lateral spacing between turbines[28].

Suitable sites for in-stream power generation are identified by performing a site-specific multivariable analysis at the municipality level over the Brazilian Amazon, taking into account the (1) extent of protected areas, (2) region's energy demand and (3) availability of TIP. Each criterion is expressed in terms of an index namely, the PAI that represents the extent of protected areas, EDI that quantifies the electricity demand not fulfilled by the country's power grid and IPI that represents the availability of in-stream potential, calculated for each municipality in the Brazilian Amazon.

The PAI is defined as the ratio of protected areas in a municipality to the total area of the municipality, which is normalized to a 0–1 scale by subtracting the minimum value from each value of the ratio and then dividing the difference by the range of percentage protected areas in the Brazilian Amazon. The PAI values are inverted by subtracting those from one because the smaller the protected areas the higher should be the development suitability.

The EDI is calculated as the mean of no-electricity household index (NEHI) and the future energy demand index (FEDI) for each municipality. NEHI is the ratio of number of households without electricity to the total number of households in a municipality normalized to a 0–1 scale. The future energy demand of a municipality is calculated using the total energy demand of Northern Brazil as reported by Operador Nacional do Sistema Elétrico (ONS), Brazil (http://www.ons.org.br/). The total energy demand of Brazil's northern sector for 2018 is distributed among the municipalities by weighing it by the distribution of population as per the 2010 Brazilian census data. Future energy demand for year 2030 is predicted by assuming a 4% increase per annum based on the linear trend of energy demand for the past years as reported by ONS. This future energy demand is then categorized into five classes: micro (<1 MW, EDI = 0.2), small (1–10 MW, EDI = 0.4), medium (10–30 MW, EDI = 0.6), large (30–1,000 MW, EDI = 0.8) and mega (>1,000 MW, EDI = 1.0). We follow the classification of dams adopted by the Brazilian government to generate EDIs for each municipality with a slight modification. We note that for better distribution of the EDI, we further sub-classify the small dam category (1–30 MW) as defined by the Brazilian government into small (1–10 MW) and medium dams (10–30 MW).

The IPI, an indicator of the available in-stream potential in a municipality, is calculated by aggregating the potential of all the model grid cells within each municipality and categorizing them following the same approach as for EDI. The available in-stream potential for the calculation of IPI is based on the 40D scenario.

Finally, the three indices (PAI, EDI and IPI) are used to assess 644 municipalities in the Brazilian Amazon and determine the suitability of the region for in-stream hydropower development. This analysis is limited to the Brazilian Amazon because most of the in-stream potential is found in the Amazonian lowlands in Brazil. Further, detailed data, such as the number of households without electricity, are only available for Brazil.

Power generation cost analysis. To assess the cost differences between storage-based hydropower and in-stream turbines, we individually estimate the cost of the nine selected planned dams in the Brazilian Amazon. Four of the selected nine dam are planned to be built in the coming decade[36] and the others are the largest planned dams in the Brazilian Amazonian. In-stream turbine cost is adopted from market value as reported for Smart Hydro Power's Smart Mono Float turbine and Smart Free Stream turbine. Life span of the in-stream turbines is assumed to be 30 yr following the information provided by the turbine manufacturers. Operation and maintenance (O&M) cost of in-stream turbines varies substantially among different case studies[40,56] on the basis of the number of operational units. In this study, we assume the O&M cost of in-stream turbines to be US$0.00047 $\mathrm{kWh^{-1}}$, which is the extrapolated O&M cost of 1,000 turbines from the trend of O&M cost against number of operational units compiled from previous case studies[40,56].

To estimate the overall cost of conventional hydropower, we use the planning tools set by the United States and Norwegian hydropower industry, which are used in the recently published literature (for example, Gernaat et al.[4]). These cost formulations (Supplementary Table 3) are functions of dam properties such as the power generation capacity, dam height and design discharge. O&M cost for storage-based hydropower is assumed as US$40 $\mathrm{kW^{-1}\,yr^{-1}}$, following the global estimates provided by the International Renewable Energy Agency (IRENA)[57]. Sub-basin-wise hydropower plant capacity factors are estimated using the power generation data of the existing dams in the Amazon basin as reported by ONS. All investments are annualized with a discount factor of 10% (ref. [4]). A life span of 50 yr is assumed for storage-based hydropower, which is higher than the common trend of using 40 yr (refs. [4,57]). We use the dam information obtained from the

ANEEL dam database as an input to these cost equations, whereas the discharge from the turbines was determined using LHF simulations. Dam heights are estimated as the difference between the upstream and downstream water levels obtained from the ANEEL database. Dam widths are derived using high-resolution (3 arcs, ~90 m) DEM from HydroSHEDS[50], as the shortest distance between the two contours representing the upstream water level in the vicinity of the dam location. Upstream inundation extent of planned dams is estimated by using high-resolution (3 arcs or ~90 m) DEM from HydroSHEDS[50] and dam height. Gridded Population of the World[58] (GPW v.4) dataset for 2020 generated by NASA's Socioeconomic Data and Applications Center (SEDAC) is used to estimate the population affected by the planned dams.

Data availability

All input datasets used in the analyses are publicly available from the cited references. Processed data required to reproduce the figures in the main text are available on CUAHSI HydroShare and Figshare (https://doi.org/10.6084/m9.figshare.13366118).

Code availability

All figures were produced using the freely available visualization libraries in Python 3.5 (such as Matplotlib). The relevant portions of the computer code used to process the results and develop the figures are available at https://doi.org/10.5281/zenodo.4382186.

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Author contributions
Y.P. and S.C. designed the research framework. S.C. conducted numerical simulations and S.C. and Y.P. analysed the results. S.C., E.B., R.Q.-A., Y.P. and N.M. developed the mathematical framework for the estimation of in-stream hydropower potential and cost comparison. E.M. contributed intellectually to the implementation of the project. S.C. prepared all graphics. All authors discussed and interpreted the results. S.C. and Y.P. wrote the manuscript. All authors discussed, commented on and edited the manuscript.

Competing interests
The authors declare no competing interests.

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