



Climate change may impair electricity generation and economic viability of future Amazon hydropower

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ABSTRACT

Numerous hydropower facilities are under construction or planned in tropical and subtropical rivers worldwide. While dams are typically designed considering historic river discharge regimes, climate change is likely to induce large-scale alterations in river hydrology. Here we analyze how future climate change will affect river hydrology, electricity generation, and economic viability of > 350 potential hydropower dams across the Amazon, Earth's largest river basin and a global hotspot for future hydropower development. Midcentury projections for the RCP 4.5 and 8.5 climate change scenarios show basin-wide reductions of river discharge (means, 13 and 16%, respectively) and hydropower generation (19 and 27%). Declines are sharper for dams in Brazil, which harbors 60% of the proposed projects. Climate change will cause more frequent low-discharge interruption of hydropower generation and less frequent full-capacity operation. Consequently, the minimum electricity sale price for projects to break even more than doubles at many proposed dams, rendering much of future Amazon hydropower less competitive than increasingly lower cost renewable sources such as wind and solar. Climate-smart power systems will be fundamental to support environmentally and financially sustainable energy development in hydropower-dependent regions.

1. Introduction

Global climate change is projected to alter water balances in many

parts of the tropics and subtropics (IPCC, 2013), where much of the world's untapped hydropower potential remains (Zarfl et al., 2015). If annual river discharges decrease or become more variable, projections

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based on historic flow records run the risk of overestimating both the magnitude and reliability of future hydropower production. Thus, while the global proliferation of hydropower dams can be a means for climate change mitigation depending on their location and design (Almeida et al., 2019b; Muller, 2019; Ocko and Hamburg, 2019), hydropower is paradoxically sensitive to the problem it is proposed to mitigate.

A global study of ~ 25,000 hydropower facilities projected negative effects of climate change on hydropower generation capacity in up to 75% of existing hydropower plants worldwide by the middle of the century (van Vliet et al., 2016). Climate change-induced alterations in hydropower generation are projected to be spatially heterogeneous across the world (Turner et al., 2017). In South America, where a large fraction of future hydropower dams may be developed (Zarfl et al., 2015), greenhouse gas (GHG) emission scenarios derived from an ensemble of 25 general circulation models (GCMs) point to substantial overall reductions in precipitation and runoff by the end of the century (Brêda et al., 2020). A large proportion of the proposed hydropower production for South America will occur in the Amazon basin, Earth's largest and most biologically diverse river system where over 350 potential hydropower dam sites with installed capacities above 1 MW have been identified (Almeida et al., 2019b). Yet, the Amazon is the region in South America where hydrologic effects of climate change tend to be most pronounced (Brêda et al., 2020).

Existing studies on the effects of climate change on Amazon hydropower have focused on Brazilian dams, and forecasted decreased hydropower production linked to overall rainfall reduction and increased frequency of prolonged droughts (Lima et al., 2014; Von Randow et al., 2019). For example, annual hydropower generation at Teles Pires—a large hydropower plant recently built in the southeastern Amazon—is expected to decrease by the end of the century across multiple climate change scenarios (Mohor et al., 2015). Reductions in discharge and consequently hydropower generation persist in the Amazon region even under basin-wide changes in land use, as has been projected for dams in Brazil's Xingu (Stickler et al., 2013), Tocantins (Von Randow et al., 2019), and Tapajós basins (Arias et al., 2020).

In order to respond to concerns over environmental damage, most future hydropower dams in the Amazon lowlands will be operated as run-of-river (i.e., downstream outflow discharges approximately equal upstream inflow discharges) (Lima et al., 2014), making hydropower generation particularly sensitive to changes in discharge (Arias et al., 2020). Ultimately, climate change-induced shifts in electricity generation may jeopardize the financial feasibility of future Amazon hydropower projects (Mendes et al., 2017). By midcentury, annual losses in hydropower revenues in Brazil's hydropower-dominant power system may exceed US\$5bn owing to anticipated climate shifts (de Queiroz et al., 2019). Large dams require significant financial investments, and ultimately these river infrastructure projects result in tradeoffs between energy production and a suite of negative social and ecological impacts (Almeida et al., 2019b; Grumbine and Xu, 2011; Latrubesse et al., 2017; Schmitt et al., 2019). Thus, forecasts of hydropower production under changing climate are critical for achieving informed energy planning that can balance energy production with negative impacts to human and nature.

While existing studies provide relevant forecasts of changing hydropower dynamics expected at a subset of projects, a spatially extensive analysis to address the diversity of climatic and hydrologic settings across the Amazon basin is lacking. Here we combine a database on 351 proposed hydropower dams throughout the Amazon basin (Almeida et al., 2019b) with bias-corrected outputs of 25 GCMs from CMIP5 (WCRP Coupled Model Intercomparison Project Phase 5) and a continental-scale hydrologic model (Brêda et al., 2020). First, we estimate climate change-induced alterations in river discharge and hydropower generation at proposed dam sites by the middle of the century (2046–2065). Then, we examine whether projected alterations in electricity generation under climate change can affect the economic competitiveness of Amazon hydropower.

2. Methods

2.1. Amazon hydropower expansion

We use a database of 351 proposed dams with over 1 MW of installed capacity in the Amazon basin (Fig. 1A) (Almeida et al., 2019b). These dams have a combined installed capacity of nearly 92 GW—three times the installed capacity of all existing Amazon hydropower dams. Brazil has the largest number of proposed dams (212), followed by Peru (85), Ecuador (36), Bolivia (16), and Colombia (2). Proposed Peruvian dams hold the largest aggregate installed capacity (34.7 GW), followed by Brazilian (33.8 GW), Ecuadorian (11.4 GW), Bolivian (11.2 GW), and Colombian (0.7 GW) dams. We refer to dams in Bolivia, Colombia, Ecuador, and Peru as dams in Andean countries. It is noteworthy that the 351 dams proposed basin-wide are in various stages of inventory, planning, and licensing. Plans to build one dam over another change constantly and are subject to technical, financial, business and political drivers. For instance, in its latest decadal energy expansion plan (Ministério de Minas e Energia, 2019), Brazil slated the construction of only three large hydropower plants (>30 MW) in the Brazilian Amazon (Bem Querer J1A, Tabajara, and Castanheira ARN120 dams); most Brazilian dams to be built over the next decade tend to be smaller-capacity ones. Small hydropower plants (defined as < 30 MW in Brazil) in advanced planning for construction are not identified by individual names, but Brazil anticipates 2100 MW of added capacity from these small projects nationwide by 2030. This would imply the construction of at least 70 small hydropower plants across the country over the next 10 years. For reference, our database contains 147 proposed Brazilian Amazon dams with installed capacities below 30 MW, which would be candidate projects for construction over the coming decade.

2.2. Projected changes in discharge

To estimate discharge changes at each proposed Amazon dam site, we used the bias-corrected outputs of 25 general circulation models (GCMs) from CMIP5 (WCRP Coupled Model Intercomparison Project Phase 5) forced into a continental-scale rainfall-runoff model (*Modelo de Grandes Bacias*, MGB) (Brêda et al., 2020). The 25 GCMs selected for our analysis were those that provide the input variables necessary to run the hydrologic model, namely surface air temperature, relative humidity, wind speed, atmospheric pressure, incoming shortwave solar radiation, and precipitation. Daily precipitation and long-term monthly means of the other climate variables were used as inputs for the hydrologic model. Although the hydrologic model provides daily outputs of evapotranspiration and runoff, we use estimates of long-term means to minimize the uncertainty associated with short-term discharge variation. Further details about the climate and hydrologic modeling are provided in Brêda et al. (2020). We compared discharges projected for 2046–2065 (“midcentury”) with a baseline period (1990–2010); late-century projections (2081–2100) are also used for comparison. Hydropower projects in South America often take more than a decade to be implemented, thus our midcentury projection period reflects anticipated conditions relevant for future built dams that are advancing through planning now. Our projections reflect two Representative Concentration Pathway (RCP) scenarios: RCP 4.5 and RCP 8.5, where 4.5 and 8.5 denote radiative forcing values (in $W\ m^{-2}$) under lower and higher atmospheric GHG emissions. RCP 8.5 represents a no-mitigation scenario in which emissions continue to rise throughout this century; RCP 4.5 represents a moderate scenario in which emissions increase until midcentury and then stabilize (Thomson et al., 2011), and is roughly consistent with a temperature rise above pre-industrial levels between 2 and 3C.

2.3. Projected changes in hydropower generation

To translate discharge changes into hydropower generation changes, we first estimated maximum and minimum usable (“turbinable”) flows

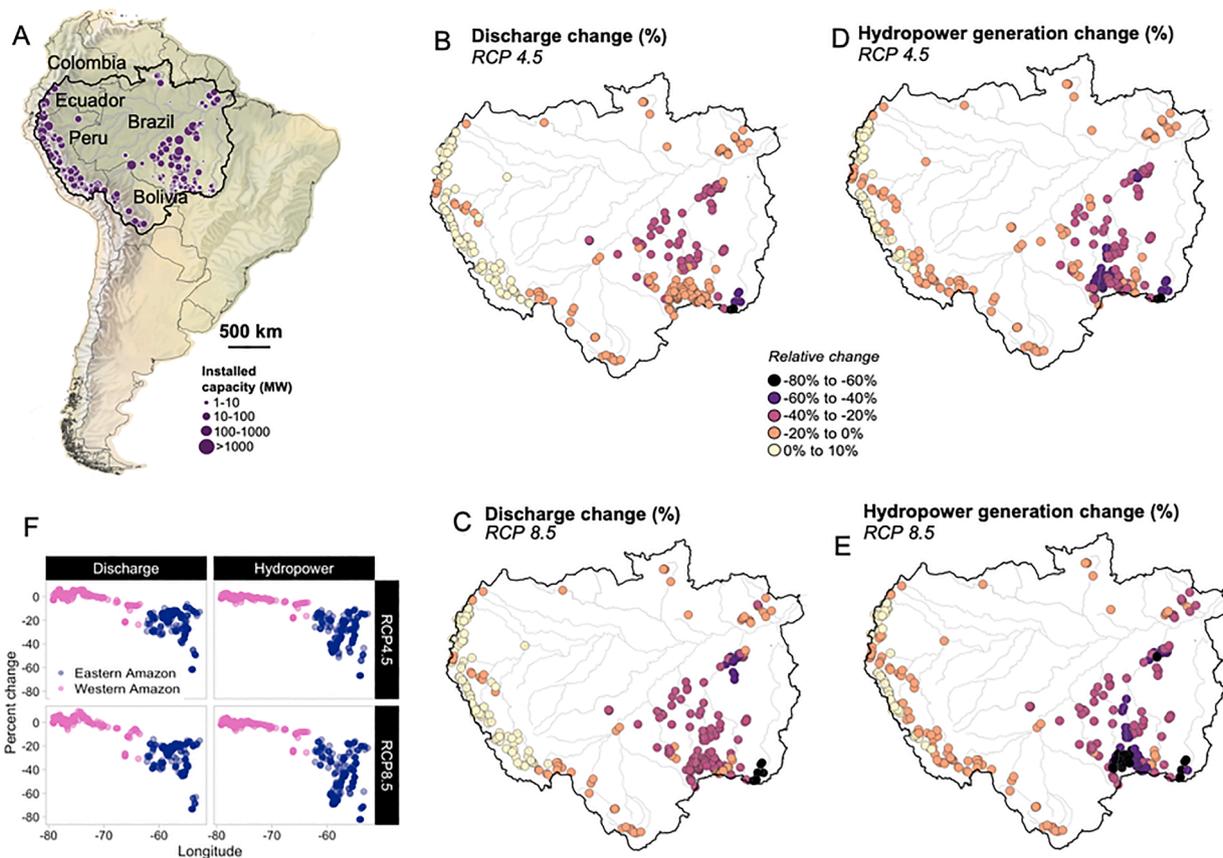


Fig. 1. Climate change effects on Amazon hydropower dams. (A) There are 351 proposed hydropower dams in the Amazon basin, totaling 92,000 MW of installed capacity. We projected mean changes in (B,C) discharge and (D,E) hydropower generation at each of these proposed dam sites by the middle of the century (2046–2065) under the RCP 4.5 and RCP 8.5 climate change scenarios. F illustrates how negative effects of climate change on discharge and hydropower generation intensify from west to east across the Amazon basin. Shaded relief map publicly available from Kenneth Townsend.

for each hydropower dam. Maximum usable flows were estimated as 1.43 times greater than mean annual flows, as derived from the relationship for modern Amazon dam projects (Fig. 2). Minimum usable flows were assumed to be the Q95 baseline flow (i.e., the discharge value

that is equaled or exceeded 95% of the time on the basis of historic baseline discharge records); this assumption is consistent with Brazil’s electricity regulatory agency guidance of hydropower projects being designed considering a 5% risk of not generating electricity (Lorey et al., 2017). To simplify the analysis, we assumed that turbine-generator efficiency is constant. We then used a linear scale between maximum and minimum usable flows to calculate hydropower generation from daily discharges considering that (1) power output is equivalent to the installed capacity at flows equal to or higher than the maximum usable flow, and (2) power output is equivalent to installed capacity * (Q95/maximum usable flow) when flows equal the minimum usable flow. There is no generation when flows drop below the minimum usable flow; flows above the maximum usable flow are released through spillways as we assumed run-of-river operation. Indeed, nearly all hydropower dams built in the Brazilian Amazon this century are operated as run-of-river (ONS, 2018), as storage dams are typically linked to environmental impediments in the environmental licensing process. This trend towards run-of-river operations is expected to hold for the future, and our underlying assumption for dam operations has been extensively adopted elsewhere (Arias et al., 2020; de Queiroz et al., 2016; Hunt et al., 2014; Lima et al., 2014). Our analysis assumes that future projects are designed based on historic flows, without consideration of climate change impacts.

We evaluated the performance of our modeled hydropower generation rates by comparing them with hydropower generation rates estimated using industry capacity factors. Industry-estimated energy generation was computed as 56% of installed capacity for dams > 30 MW and 61% for dams < 30 MW, which are based on data from 145 Brazilian hydropower dams > 30 MW and 352 dams < 30 MW (Prado

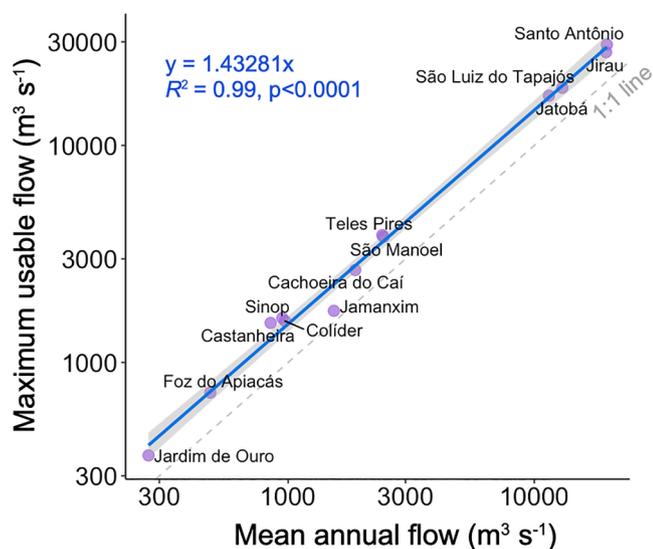


Fig. 2. Relationship between mean annual flow and maximum usable flow. Regression through the origin between maximum usable flow and mean annual flow for 13 modern hydropower dams recently built or planned for the Amazon basin.

and Berg, 2012). These capacity factors are consistent with the standard capacity factor (55%) recommended by Brazil's Ministry of Mines and Energy for hydropower inventory studies of river basins (Brazil Ministry of Mines and Energy, 2010), as well as the weighted-average capacity factor of hydropower dams globally (49%) (IRENA, 2019). We observed strong agreement between hydropower generation rates calculated using our model and typical plant capacity factors (Fig. 3).

2.4. Economic feasibility analysis

To gauge whether climate change-induced alterations in hydropower generation could substantially affect economic feasibility, we estimated the levelized cost of electricity (LCOE) of each proposed Amazon dam under baseline, RCP 4.5 and RCP 8.5 scenarios. Our economic analysis assumes all projects are built to current specifications. The LCOE is an indicator of competitiveness, providing the minimum unit price of electricity for an energy project to break even on all investment, maintenance, and operation costs over a given cost recovery time horizon. The LCOE was calculated as follows:

$$LCOE = \frac{\sum_{t=0}^T (I_t + M_t)(1+r)^{-t}}{\sum_{t=0}^T (E_t)(1+r)^{-t}}$$

where I_t is the investment expenditure (civil works and electro-mechanical equipment) in year t , M_t is the operation and maintenance (O&M) expenditure in year t , E_t is the total amount of electricity generated in year t , T is the cost recovery horizon, and r is the economic discount rate. We used a discount rate of 10%, which is the standard value used by the International Renewable Energy Agency (IRENA) for non-OECD countries in their 2019 report on Renewable Power Generation Costs (IRENA, 2019). We also followed IRENA on setting hydropower's O&M expenditures to 2% of the investment cost per year (IRENA, 2019). We consider a cost recovery horizon of $T = 20$ years, matching the horizon of our climate change projections and in agreement with cost recovery periods commonly adopted in financial analysis of renewable energy projects (IRENA, 2019). Investment expenses accrue in $t = 0$ and operation starts at $t = 1$. Investment costs ($\$ \text{ kW}^{-1}$) vary according to project size and across regions. In our main analysis,

we used weighted-average investment costs reported by IRENA for recently constructed hydropower dams in Brazil and other South American countries (IRENA, 2019). For Brazilian dams, we used IRENA's weighted-average for Brazil ($2,364 \text{ \$ kW}^{-1}$ for installed capacities $< 10 \text{ MW}$ and $1,460 \text{ \$ kW}^{-1}$ for installed capacities $> 10 \text{ MW}$). For dams in Andean countries, we used IRENA's weighted average for South America ($2,321 \text{ \$ kW}^{-1}$ for installed capacities $< 10 \text{ MW}$ and $2,029 \text{ \$ kW}^{-1}$ for installed capacities $> 10 \text{ MW}$).

We ran a sensitivity analysis considering alternative discount rates and investment costs. For the discount rate, we considered lower and upper bounds as the lowest (2.5%) and highest (12.6%) values reported in a recent review on the cost of capital for renewable energy projects worldwide (Steffen, 2020). For investment costs of hydropower, we considered the lower and upper bounds as the 5th and 95th percentiles of investment costs reported by IRENA for Brazilian dams $< 10 \text{ MW}$ ($2,051\text{--}2,823 \text{ \$ kW}^{-1}$) and $> 10 \text{ MW}$ ($1,045\text{--}3,479 \text{ \$ kW}^{-1}$), and South American dams $< 10 \text{ MW}$ ($1,924\text{--}3,966 \text{ \$ kW}^{-1}$) and $> 10 \text{ MW}$ ($1,539\text{--}3,694 \text{ \$ kW}^{-1}$) (IRENA, 2019).

We compare the LCOEs of Amazon hydropower to average LCOEs of onshore wind and solar photovoltaics. We adjusted LCOE calculations for solar and wind according to the payback horizon ($T = 20$ years) and discount rate ($r = 10\%$) of our analysis. To calculate the LCOE of solar and wind, we used IRENA's global weighted-average investment costs (solar photovoltaics = $995 \text{ \$ kW}^{-1}$, onshore wind = $1,473 \text{ \$ kW}^{-1}$), capacity factors (solar photovoltaics = 18%, onshore wind = 35.6), and O&M costs (solar = $9.5 \text{ \$ kW}^{-1}$ per year, onshore wind = $0.02 \text{ \$ kWh}^{-1}$ per year) (IRENA, 2019). For solar photovoltaics, O&M costs are the weighted average of non-OECD countries. For onshore wind, O&M costs are the upper bound of the reported ranges, and we converted generation-based to capacity-based O&M using average capacity factors.

3. Results and discussion

3.1. Changes in river discharge

For the Amazon as a whole, there is an overall trend of decreased midcentury discharge at proposed dam sites (median change: -13% under RCP 4.5 and -20% under RCP 8.5) (Fig. 1B,C and Fig. 4A). However, projected changes in discharge at proposed dam sites vary widely across the basin, ranging from strongly negative in the east to slightly positive in the west (Fig. 1 and Fig. 4). In the Brazilian Amazon, projected discharge change is negative for all proposed dams under either RCP 4.5 (median change: -18%) or RCP 8.5 (-23%) (Fig. 4A). By contrast, the projected discharge change is positive for $\sim 65\%$ of proposed dam sites in Andean Amazon countries under both RCP scenarios (median change: 1.5% for RCP 4.5 and 2.5% for RCP 8.5) (Fig. 4A). These projections of a wetter western Amazon (Andean Amazon) and a drier eastern Amazon concur with most regional (Marengo et al., 2009; Ribeiro Neto et al., 2016; Sorribas et al., 2016) and global-scale studies (Asadieh and Krakauer, 2017; Koirala et al., 2014; Schewe et al., 2014).

3.2. Changes in hydropower generation

The spatial trends for hydropower generation change resemble those for discharge, with substantial reductions in the Brazilian Amazon compared to modest changes in dams proposed for Andean countries (Fig. 1D,E and Fig. 4B). Importantly, however, projected hydropower generation in Brazil is disproportionately lower than anticipated discharge decreases (Fig. 4C). The non-linearity between changes in discharge and hydropower generation is associated with the fact that dams are not designed to utilize all possible discharges of the flow regime to generate electricity. In other words, dams have usable ("turbineable") flow bands, whereby discharges exceeding the maximum usable flow are spilled (or stored in reservoirs, when dams are not operated as run-of-river) and turbines do not operate when discharges drop below a minimum value. Under hydrologic regimes with higher seasonal

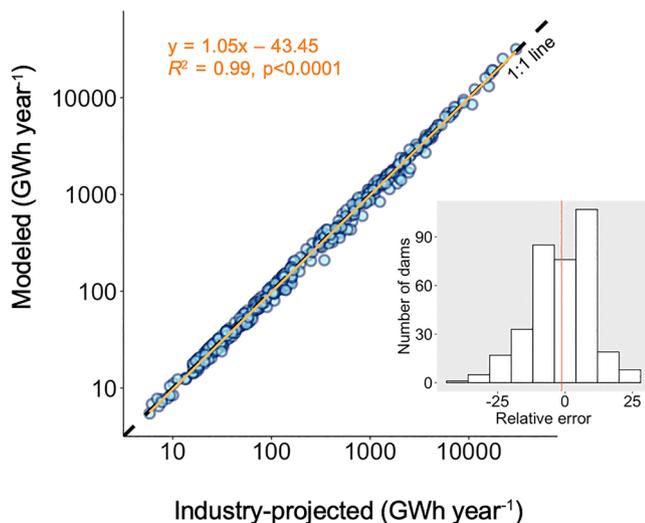


Fig. 3. Industry-projected hydropower generation at the 351 proposed dams versus our modeled generation estimates. Industry-projected generation was estimated using average plant capacity factors and our model was run using baseline discharges (1990–2010). The inset histogram reveals that the relative errors of the model with respect to industry projections are normally distributed, with the average (red line) being close to zero. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.) (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

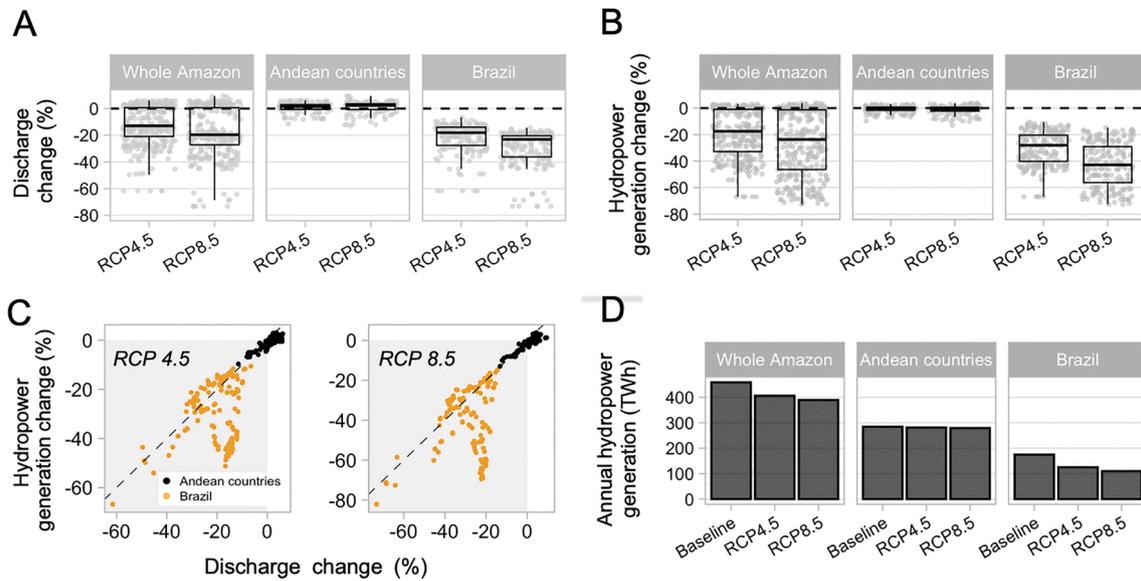


Fig. 4. Changes in river discharge and hydropower generation in the Amazon basin are regionally variable. Boxplots depict the percent change in (A) discharge and (B) hydropower generation under RCP 4.5 and RCP 8.5 with respect to baseline (i.e., current hydrological conditions). Discharge estimates are derived from a hydrological model forced with an ensemble of 25 general circulation models (Brêda et al., 2020). Projections are for the middle of the century (2046–2065). Each dot is the ensemble median for one proposed hydropower dam site. Graphs are shown for the whole Amazon basin (n = 351 dams) as well as separately for the group of Andean countries (Bolivia, n = 16; Colombia, n = 2, Ecuador, n = 36; and Peru, n = 85) and Brazil (n = 212). (C) Hydropower generation change plotted against discharge change indicates greater loss of energy generation potential for Brazilian Amazon dams; the dashed line indicates a reference 1:1 line. (D) Aggregate annual midcentury hydropower generation of all proposed dams under baseline and RCP 4.5 and RCP 8.5 scenarios.

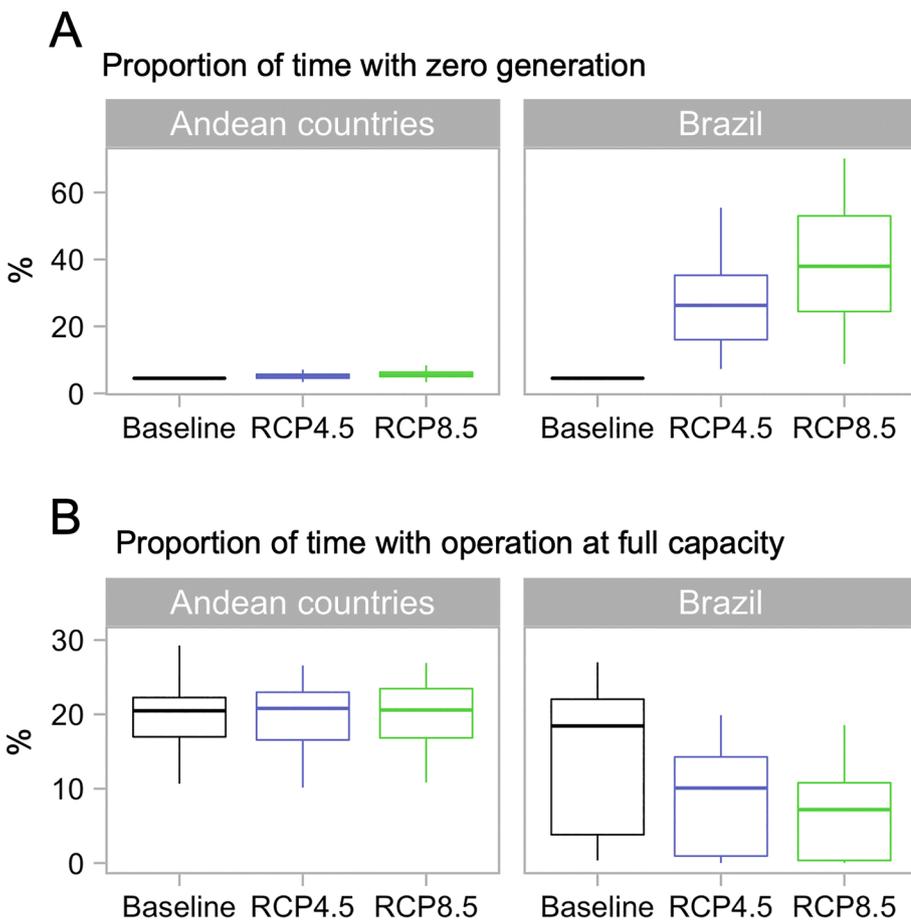


Fig. 5. Changes in the frequency of usable flows. Boxplots depicting the proportion of time that proposed Amazon dams in Andean countries and Brazil remain with (A) flows below minimum usable flow and (B) flows above maximum usable flow, considering discharge regimes under baseline and the RCP climate change scenarios. Flows below the minimum usable flow result in zero hydropower generation, whereas dams generate energy at full installed capacity when flows are equal to or exceed the maximum usable flow.

amplitude, low flows may be lower, and high flows may more often exceed the turbinable range and thereby not generate more electricity. While usable flow patterns at dams in Andean Amazon countries are unlikely to be altered substantially (Fig. 5), the proportion of time with usable flows in Brazil will be much shorter under climate change as a consequence of flows being more often below the required minimum flow for turbine operation (Fig. 5A) and dams operating at full capacity less frequently (Fig. 5B).

When scaled up across proposed dams, unequal distribution of changes in hydropower production among countries emerge. For example, under a full build-out scenario where all proposed dams are implemented, Andean countries experience negligible losses of hydropower generation from new dams under both RCPs as compared to current hydrologic conditions (Fig. 4d). In contrast, annual hydropower generation from the full build-out portfolio of Brazilian dams decreases by 28% (RCP 4.5) and 37% (RCP 8.5) relative to the full build-out with current hydrology (Fig. 4d). In the Amazon as a whole, annual hydropower generation from the full build-out portfolio of proposed dams could decrease by 12% under RCP 4.5 and 15% under RCP 8.5 (Fig. 4d). Impairment of basin-wide hydropower generation is expected to aggravate towards the end of the century, with nearly 90% of proposed Amazon dams projected to generate less hydropower under late-century (2081–2100) discharges compared to midcentury (2046–2065) discharges (Fig. 6).

The results from our basin-scale analysis concur with smaller scale findings for dams in the Amazon reported elsewhere (Arias et al., 2020; de Queiroz et al., 2019; Stickler et al., 2013). A modeling study for a run-of-river hydroelectric power plant recently built in the Brazilian Amazon suggests that hydropower generation can decrease even under increased annual rainfall because high flows can exceed the installed capacity, whereas the projected increased duration of low-flow periods results in more time below the required minimum flow for turbine operation (Mohor et al., 2015). Changes in mean discharge may thus translate into increased spillway discharge and relatively small changes in flow

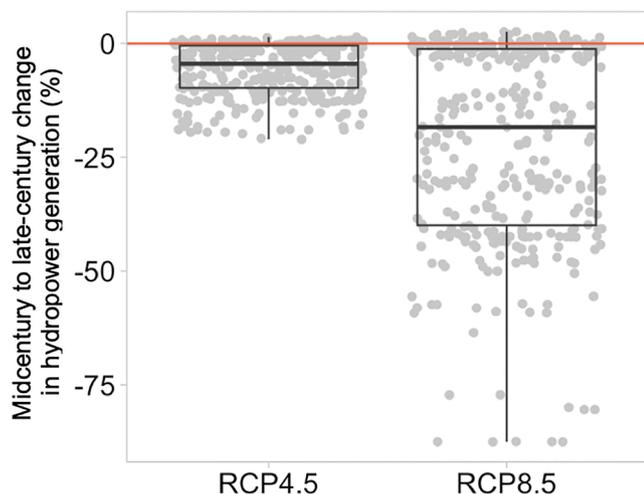


Fig. 6. Late-century versus midcentury hydropower generation. Our core analysis focuses on climate change effects on Amazon hydropower between 2046 and 2065 (midcentury), reflecting early lifetime stages of the proposed projects. Given significantly negative effects on Amazon hydropower already observable by midcentury, we used published discharge estimates for 2081–2100 (late century) to understand whether effects on hydropower generation will be exacerbated or attenuated by late century. Boxplots show the percent change in projected hydropower generation at proposed Amazon dam sites for late century relative to midcentury. Each point represents one dam. Negative values mean that annual hydropower generation is projected to be lower at the end of the century compared to midcentury. In over 85% of all proposed dams the negative effects of climate change on hydropower generation will be amplified later in the century compared to midcentury.

through turbines, because run-of-river operations would imply that excess flow cannot be utilized for electricity generation (Arias et al., 2020). This decline in annual production could also be experienced if the annual discharge remains the same, but increased rainfall variability produces increased flow during high-flow periods whereby excess water has to be spilled.

3.3. Economic viability

We next evaluated whether midcentury changes in hydropower generation could affect the economic viability of proposed Amazon dams. For the three hydropower generation scenarios (baseline, RCP 4.5 and RCP 8.5), we calculated the LCOE ($\$ \text{MWh}^{-1}$), a metric useful for comparing the economic competitiveness of energy projects with similar power system services (Joskow, 2011) (i.e., here, intermittent renewable electricity generation). The LCOE provides the average unit cost of generating electricity over a cost recovery period, which commonly varies between 20 and 30 years for renewable energy projects (IRENA, 2019). In other words, the LCOE can be viewed as the electricity sale price needed for a hydropower project investment to break even.

Consistent with the negligible discharge changes under the RCP scenarios, the LCOE of dams in Andean countries would not be

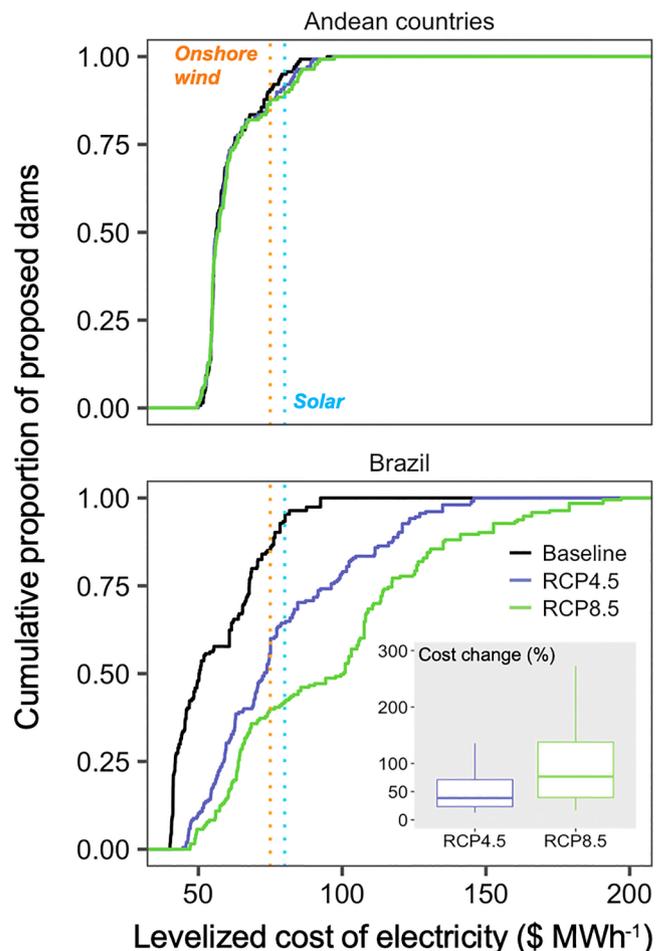


Fig. 7. Economic competitiveness of Amazon hydropower under climate change. Cumulative proportion of proposed Amazon dams in Andean countries and Brazil as a function of the levelized cost of electricity (LCOE) under baseline and RCP 4.5 and RCP 8.5 climate change scenarios. Results show potentially sharp increases in the LCOE of Brazilian dams under changing climate. The inset in Brazil's panel shows the relative cost increment of Brazilian dams under the RCP scenarios relative to baseline. The vertical dotted lines show the average LCOE of onshore wind and solar power plants globally; hydropower LCOE values above these values indicate weaker economic competitiveness.

substantially affected by climate change (Fig. 7). Conversely, decreased hydropower generation under climate change would greatly increase the LCOE of dams in the Brazilian Amazon (Fig. 7). In Brazil, the average LCOE of proposed dams becomes 52% (standard deviation = 43%; median = 39%) higher under RCP 4.5 and 105% (standard deviation = 96%; median = 77%) higher under RCP 8.5. Notably, the LCOE of three quarters of the proposed Brazilian dams could increase by at least 40% under RCP 8.5, and more than double in over a third of them (Fig. 7).

Our findings of increased hydropower production costs at proposed Brazilian dams under the RCP scenarios hold true for a wide range of alternative installation costs and economic discount rates (Fig. 8). Ultimately, increased LCOE may reduce the economic competitiveness of many Brazilian Amazon dams relative to the lowest-cost renewable energy alternatives, namely onshore wind and solar photovoltaics (Fig. 7). As an example, >80% of proposed Brazilian dams would be more competitive in terms of LCOE than onshore wind if historic river discharges persist to midcentury, but this percentage drops to ~ 40% under the RCP 8.5 scenario (Fig. 7). Remarkably, our estimates reflect installation costs as of 2019 and do not consider that costs of wind and solar power, unlike hydropower, are dropping sharply (Fig. 9). Continued technological advancements and increasing economies of scale are likely to sustain these cost reduction trends of solar and wind

power (ESMAP, 2019; IRENA, 2016). The U.S. Department of Energy projects a decline of 40–70% and 20–60% in the LCOE of solar photovoltaics and onshore wind, respectively, by 2045 compared to 2019; conversely, hydropower costs are projected to remain unchanged (NREL, 2020). It is thus highly likely that prices for non-hydropower renewables will be even more competitive in the next decade or two, when many of the proposed Amazon hydropower dams would be slated for construction.

4. Conclusions

Our analyses depict outcomes under a scenario where no action is taken to design future hydropower projects that are resilient to changing hydrologic regimes. We find that if proposed Amazon dams are built to current specifications assuming historic discharge regimes, hydropower generation and economic viability may be seriously compromised under changing climate conditions by the middle of the century. To balance the benefits and costs of hydropower dams—the latter of which extend beyond economic costs and include a suite of ecosystem impacts—energy planners must explicitly account for climate risks in making decisions to build proposed Amazon hydropower plants.

Our analysis assumed a general operation rule consistent with the

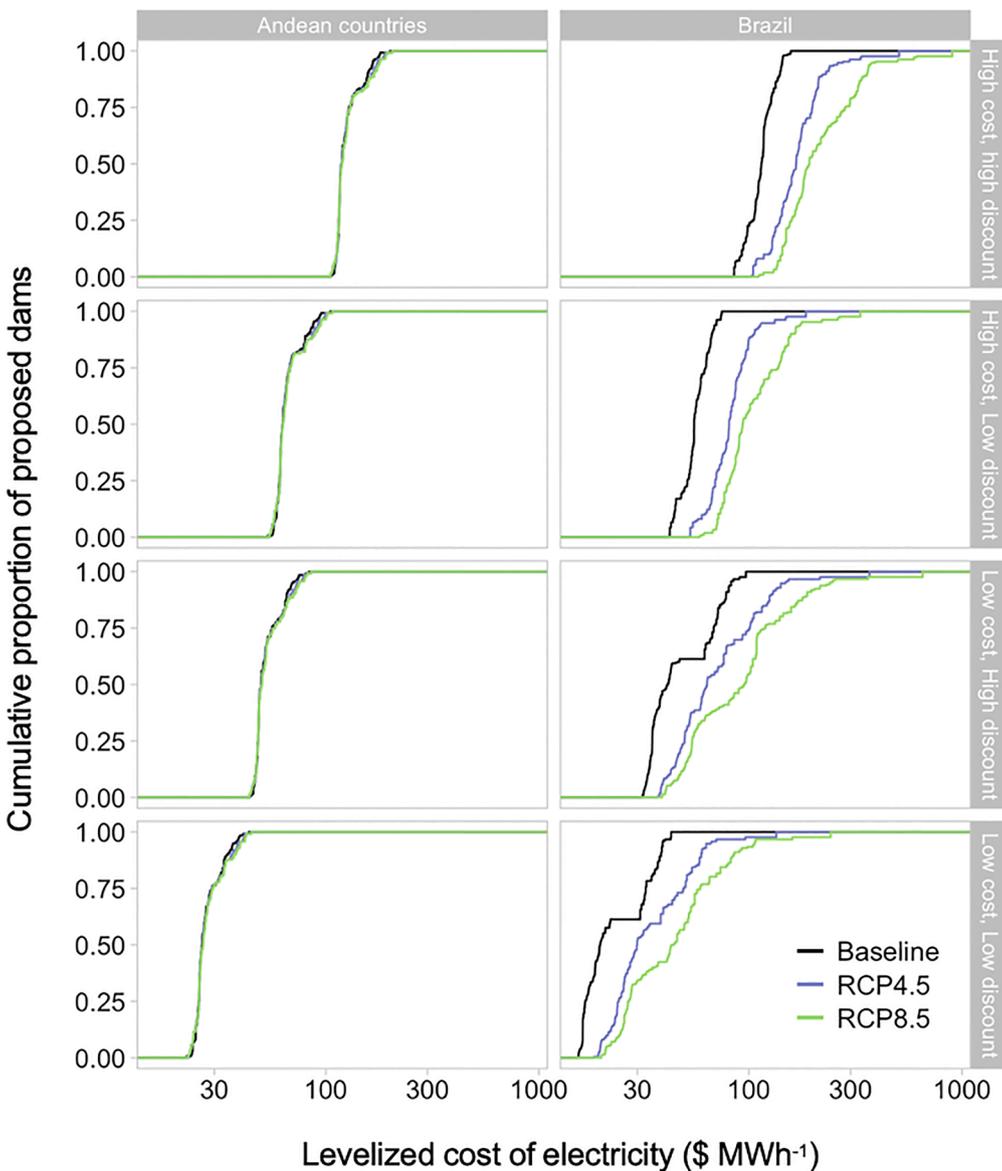


Fig. 8. Sensitivity analysis of the levelized cost of electricity (LCOE). Two-by-two sensitivity analysis of the LCOE of proposed hydropower dams in Andean countries and Brazil under baseline, RCP 4.5 and RCP 8.5. We varied the investment cost and discount rate parameters. Low and high discount rates refer to the lowest (2.5%) and highest (12.6%) values reported in a recent review on the cost of capital for renewable energy projects globally. Low and high investment costs are defined as the 5th and 95th percentiles of investment costs reported by the International Renewable Energy Agency (IRENA) for dams in Brazil and South America. The horizontal axis is on a log scale for improved visualization.

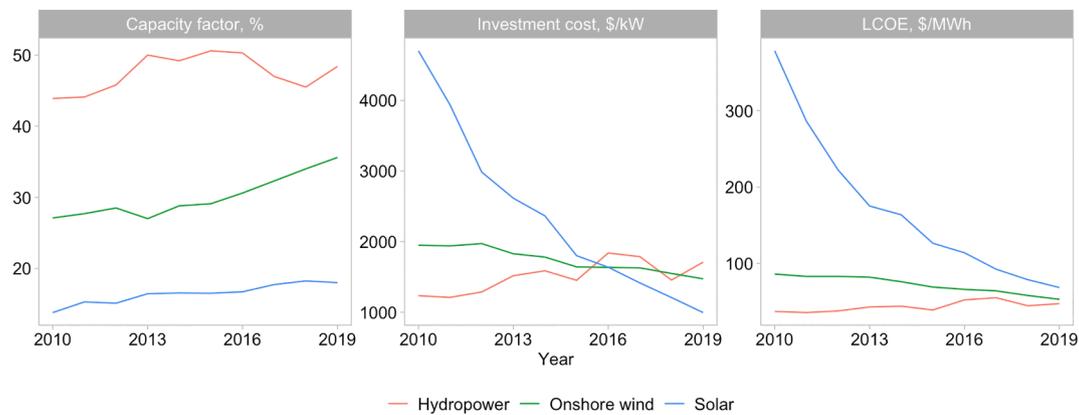


Fig. 9. Cost trends of renewable energy sources. Annual change in average plant capacity factor, investment cost and levelized cost of electricity (LCOE) of global hydropower, onshore wind, and solar photovoltaics between 2010 and 2019. LCOE of global onshore wind and solar power plants is decreasing due to a combination of increased capacity factors and decreased investment costs. Conversely, the LCOE of hydropower has displayed a growing trend between 2010 and 2019. Source: International Renewable Energy Agency.

fact that most future hydropower dams built in the Amazon are expected to be operated as run-of-river due to a range of environmental impediments associated with the construction of storage dams and regulation of seasonal flows. Notably, we find that run-of-river designs are ineffective in buffering from increased occurrence of extreme low flows in the eastern Amazon in the future. Site-specific adaptation in project designs and system-wide optimization of operations would be necessary. Indeed, optimized operation of run-of-river dams in the Brazilian Amazon with increased flow regulation during critical months can attenuate potential deforestation- and climate change-induced hydropower losses (Arias et al., 2020).

The construction of reservoirs with large storage potential has been alternatively suggested as a strategy to adapt for increased climatic variability in the Amazon (Soito and Freitas, 2011). Yet the fact that making Amazon hydropower more resilient to climate change is associated with increasing storage and flow regulation creates a problematic trade-off. Increased energy security provided by larger storage and flow regulation may be counterbalanced by the amplification of negative environmental impacts, including substantial disruptions in the flow of sediments and nutrients essential for floodplain evolution and productivity (Almeida et al., 2019a; Forsberg et al., 2017), intensification of natural flow regime alterations (Timpe and Kaplan, 2017), decreased fisheries yield downstream (Forsberg et al., 2017), augmented local species extinction following inundation of biologically diverse terrestrial habitats (Benchimol et al., 2015), and exacerbation of GHG emissions per unit electricity generated (Almeida et al., 2019b). Large reservoirs are also associated with increased displacement of human populations and loss of livelihoods, including direct and indirect impacts on indigenous communities (Athayde et al., 2019). Another challenge for creation of storage reservoirs is that many potential dam locations in Brazil are not in steep valleys, and thus a very large amount of land may have to be flooded (Hunt et al., 2014).

Achieving climate-resilient hydropower generation in regions of the Amazon anticipated to experience climate-driven hydrologic changes may represent a challenging design paradox. Pursuing run-of-river hydropower may be preferable for attenuating negative ecological impacts from dams, but may not be viable from energy security and financial standpoints. In contrast, large reservoirs may buffer against future hydrologic change, but increased storage and flow regulation may lead to ecosystem impacts that could make projects unviable from an environmental sustainability perspective. In light of this potential impasse, continued investments in non-hydropower renewable energy may grow in importance (de Lucena et al., 2010; Ministério de Minas e Energia, 2019), particularly considering that Amazon hydropower is expected to become financially less competitive relative to other renewables with

climate change. Potential for exploitation of non-hydropower renewables in Amazon countries is large (Cevallos-Sierra and Ramos-Martin, 2018; de Jong et al., 2019; IRENA, 2014; Zegada, 2016). This is especially true for Brazil, the Amazon country whose hydropower potential is most vulnerable to climate change and where the vast majority of future demand for electricity among Amazon countries concentrates (Fig. 10). Onshore wind energy potential in Brazil has been estimated to exceed 500 GW—over five times the combined installed capacity of all proposed Amazon dams in our database (de Jong et al., 2019). Unlike Amazon run-of-river hydropower, Brazil's wind energy generation potential may grow under projected climate changes, whereby increased wind speeds may cause late-century Brazil's wind generation to nearly double compared to baseline (de Jong et al., 2019). Offshore wind also has massive potential in Brazil, exceeding 1200 GW (ESMAP, 2019)—nearly 30% of the current total installed capacity of fossil-fueled power plants globally. Although still more expensive than other renewables, offshore wind projects are expected to become increasingly competitive as the market grows (ESMAP, 2019). Hydropower development in the Amazon has been viewed as a financial and environmental path to energy security. However, such development carries with it large risks emerging from consensus projections of reduced future river discharge, which may ultimately reduce energy security, erode economic competitiveness, and cause unneeded environmental harm.

CRedit authorship contribution statement

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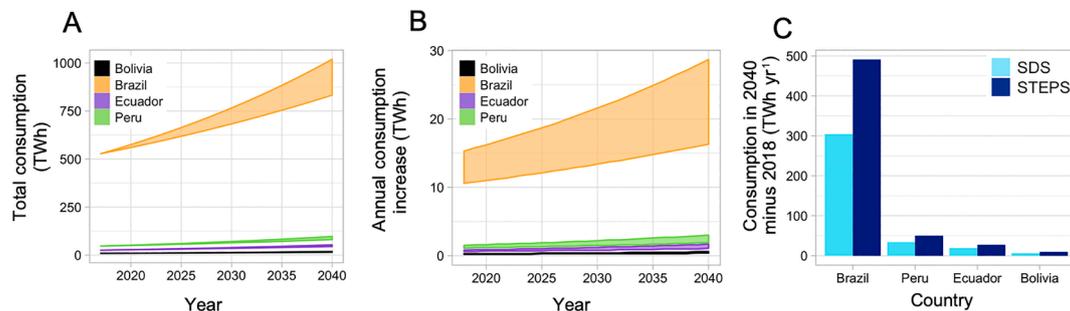


Fig. 10. Projected electricity consumption trends in Bolivia, Brazil, Ecuador, and Peru between 2018 and 2040. (A) Total electricity consumption, (B) annual increase in electricity consumption, and (C) total increase in annual electricity consumption in 2040 relative to 2018. Electricity consumption as of 2017 was downloaded from the website of the International Energy Agency (IEA). Electricity consumption trends between 2018 and 2040 were then calculated assuming annual growth in electricity demand considering two IEA scenarios, Stated Policies (STEPS) and Sustainable Development (SDS). Between 2018 and 2040, we assumed projected annual growth rates in electricity demand of 2.0–2.9% (SDS-STEPS) for Brazil and 2.4–3.2% (SDS-STEPS) for Bolivia, Ecuador, and Peru. In (A) and (B), the lower and upper bounds refer to SDS and STEPS projections, respectively. Even with lower annual growth rates, Brazil is by far the country with most future demand. Between 2018 and 2040, Brazil is likely to need nearly 10 times more electricity than Peru, the second country with largest increase in demand.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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