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Climate impacts on hydropower and consequences for global electricity supply investment needs

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ABSTRACT

Climate change is projected to increase hydropower generation in some parts of the world and decrease it in others. Here we explore the possible consequences of these impacts for the electricity supply sector at the global scale. Regional hydropower projections are developed by forcing a coupled global hydrological and dam model with downscaled, bias-corrected climate realizations. Consequent impacts on power sector composition and associated emissions and investment costs are explored using the Global Change Assessment Model (GCAM). We find that climate-driven changes in hydropower generation may shift power demands onto and away from carbon intensive technologies. This causes significantly altered power sector CO_2 emissions in several hydro-dependent regions, although the net global impact is modest. For drying regions, we estimate a global, cumulative investment need of approximately one trillion dollars (±\$500 billion) this century to make up for deteriorated hydropower generation caused by climate change. Total investments avoided are of a similar magnitude across regions projected to experience increased precipitation. Investment risks and opportunities are concentrated in hydro-dependent countries for which significant climate change is expected. Various countries throughout the Balkans, Latin America and Southern Africa are most vulnerable, whilst Norway, Canada, and Bhutan emerge as clear beneficiaries.

1. Introduction

Almost a fifth of the world's electrical power supply depends directly on the potential energy of water delivered to catchment headwaters by the climate system. The number of countries developing capacity to harness this power through dam construction is growing [1]. Hydroelectric dams are seen by governments as a means to stimulating economic growth through the provision of clean, renewable energy, as well as a host of other benefits including flood control and water supply for agriculture and industry [3]. At least 3700 major dams (>1 MW installed capacity) are either under construction or in planning across the developing world [55]). These projects not only ensure that hydropower will remain a vital component of global electricity supply through the 21st century; they also expose electricity supply networks to risks and opportunities associated with climate change.

Climate change is projected to manifest in alterations to the spatial and temporal distribution of water availability throughout the world [4,56,5–7]. Some river basins will receive less precipitation on average; others will receive more. Hydroelectric power production at dams located on affected rivers will be impaired or enhanced accordingly—demonstrated neatly by a sharp fall in hydropower production in California during a recent prolonged drought [8]. New tools have advanced our ability to study these potential impacts at the global scale. These include the latest generation of General Circulation Models and downscaling methods, Global Hydrological Models and river routing techniques [9], and detailed datasets specifying the locations and properties of hydropower facilities, including turbine, dam and reservoirs specifications [10–12]. Top-down climate impact assessments that have deployed these tools highlight significant potential impacts of climate change on 21st century hydropower production across many world regions [13–16]. These studies and their underpinning methodologies can be considered a success in that results are corroborated reasonably well by a tranche of finer-detailed, localized assessments examining possible climate impacts on hydropower in specific river basins, countries and regions (e.g., [17–27]). As yet, however, we know of no global scale study that has taken the next logical step of examining the consequences of long-term

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losses or gains in hydropower production on the electricity supply sector (herein termed “power sector”). And whilst it has been shown that climate-driven changes in hydropower production could impose significant change on planning-relevant variables through alterations to the operations of a given system [28], similar implications arising from required long-term changes in the technological composition of the power sector remain unexplored at a global scale. For some regions, these changes could create non-trivial planning and policy problems relating to the costs of power generation and associated emissions [29].

In this study, we explore potential impacts of gains and losses in hydropower generation on the technological composition of the power sector and consequent effects on 21st century carbon emissions and investment costs of new capacity. Impacts on global emissions are interesting because they may indicate the presence a reinforcing effect. Emissions drive greenhouse warming, which may intensify drying in basins important for hydropower generation. This loss of hydropower production could shift the generating composition of the power sector toward more carbon-intensive technologies, thereby driving further climate change. Such a feedback loop would be moderated by an opposing negative feedback occurring in regions experiencing increased precipitation. Nonetheless, exploring the plausibility of this phenomenon would seem prudent given the potential threat it raises. With regards impacts on power sector investments, regions that depend heavily on hydropower to meet electrical energy needs may be particularly vulnerable, because lost generating capacity implies that investments in alternative generating technologies will be required to meet growing demands for electricity. These investment risks could be affected by globally-agreed emissions targets—such as those defined under the Paris Agreement [30]—because sustained shortfalls in hydropower generating capability may have to be addressed through increased investment in expensive, low-carbon technologies to ensure nationally defined contributions are met. The relevant policy-makers ought to be attuned to these effects and the implications they carry for power sector planning and investment strategy—particularly in countries with relatively low capacity to raise finance for new capital works.

2. Method

We study the impacts of climate change on hydropower production and then power sector composition for 32 distinct world regions. This is achieved in two main steps. First, we generate hydropower projections for each region by forcing a coupled global hydrological and hydropower dam model with gridded GCM climate projections for the 21st century. Second, we feed these projections into an integrated assessment model to explore how the power sector might adapt to changes in hydropower production at each world region. We repeat both steps of the experiment for two alternative future scenarios: a baseline scenario in which no measures are introduced to reduce emissions (*RCP8.5* scenario, [31]); and a scenario for which a global value on carbon is implemented to limit radiative forcing at 4.5 W/m^2 by 2100 (*RCP4.5* scenario, [32]). These scenarios are from the Representative Concentration Pathways (RCPs) [33], developed for long-term climate modeling experiments and adopted in the Intergovernmental Panel for Climate Change 5th Assessment Report.

2.1. Hydropower impact model

Climate change impacts on hydropower are developed for 32 global regions using 21st century climate projections from sixteen General Circulation Models (GCMs). Specifically, we use Bureau of Reclamation downscaled and bias corrected CMIP5 climate projections of precipitation and temperature at 0.5° × 0.5° grid cells and monthly temporal resolution [34]. These data are used to force a Global Hydrological Model (GHM) to generate streamflow for the period 1950–2100 (same spatial and temporal resolution). The GHM applied here is the Global Water Availability Model (GWAM) [35]. GWAM represents the soil water flux in each grid to simulate monthly runoff. Runoff is accumulated and routed along river channels using a modified version of the River Transport Model (RTM) [36,37] to derive streamflow data, which are validated by comparing with both observations [57] and other GHMs (documented in Ref. [35]. The streamflow data are used to construct reservoir inflow time series for 1593 large dams. These dams and the associated reservoir and plant properties are taken from the Global Reservoir and Dam database [12] with gaps infilled from auxiliary datasets [10,11]. Reservoir inflows are computed by multiplying accumulated grid cell streamflow by a small correction factor to account for any discrepancy between reported upstream catchment area and that implied by aggregated upstream grid cells. All dams are then simulated using a global hydropower dam operating model that accounts for reservoir storage behavior, evaporation losses, power plant properties (e.g., maximum turbine work rate), and typical reservoir bathymetry [38,39]. The model applies a classical optimization technique known as stochastic dynamic programming to define realistic, bespoke turbine release rules for each dam [40]. With release rules in place, reservoirs are simulated using the well-established storage behavioral analysis technique based on mass balance [41]. This detailed dam and reservoir modeling approach was found to be advantageous for impact studies because it captures non-linearity of long-term changes in power production in response to climate change [15]. Causes of non-linearity captured by this model include maximum turbine work rate, which can limit power production in wetter climates, and reservoir surface evaporation, which can exacerbate the deterioration of production in drier climates. The modelled dams represent more than half of global installed hydropower capacity and are well distributed spatially throughout the world (Fig. 1). Operations for all dams target maximum hydropower production, subject to an environmental flow constraint defined using the variable monthly flow method [42]. This approach overlooks the fact that most of the world's installed hydro competes with other demands for stored water—particularly irrigation [43]. Despite this omission, previous validation work has shown that country-level, annual hydropower generation is captured remarkably well by our model (see Ref. [15]).

The model chain described above produces monthly projections of energy production for all dams. These are aggregated to estimate regional, annual energy production, and then smoothed using a Lowess technique [44] to remove inter-annual variability. Absolute energy (TWh/yr) is transformed to relative change (%) from the mean of a 30-year time slice centered on 2010. The projections are then superimposed onto 21st century hydropower capacity expansion trajectories, predetermined for each region using estimates from the International Hydropower Association [45] and various World Bank sources [46].

An implicit assumption of the above approach is that new dams built throughout the 21st century will be subject to the same climate signal as those dams installed already within each region. This assumption may not hold true in all instances, particularly for developing countries where many potential dam sites have yet to be exploited. A more coherent approach would be to model both climate change and capacity expansion simultaneously, bringing new dams online as and when they are constructed during the 21st century. Such an approach would require data outlining where dams are to be built, when they will be operational and what specifications they will have. These details are generally

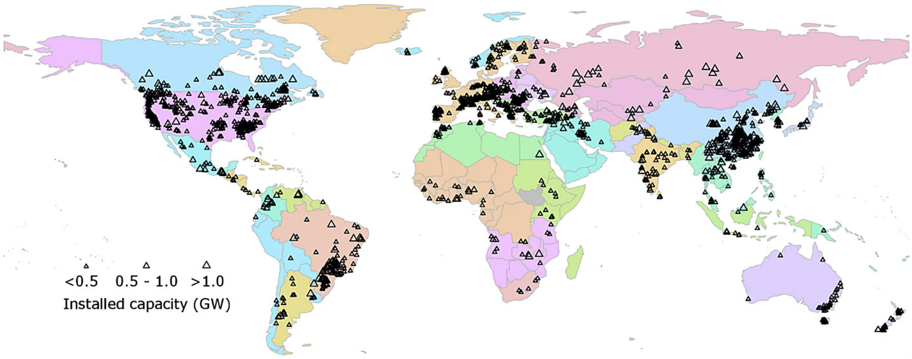

Fig. 1. Locations of 1593 hydropower dams used to simulate 21st century regional hydropower production with alternative climate forcing realizations. Countries are grouped into the 32 GCAM regions by colour. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

unavailable or far too uncertain to include in a global study of this nature. And since a substantial portion of new dams will be built in basins that have already been exploited for hydropower to some degree, we believe the pursued approach will return reasonable estimates of climate change impacts on 21st century regional hydropower production.

2.2. Integrated assessment model

Hydropower capacity expansion estimates are used as a fixed input to the Global Change Assessment Model (GCAM). GCAM is a Representative Concentration Pathway (RCP)-class, dynamic-recursive model designed for exploring implications of climate and energy policy on economies, energy systems, land use, food, and water. The model applies some basic assumptions relating to socioeconomic change (e.g., population growth, labor participation and productivity) to drive demands for energy and land resources, which are balanced by retiring and adding various technology options, including electricity generating facilities. These technologies are selected according to their relative costs using a logit-choice formulation, which avoids the unrealistic situation of a single cheapest technology dominating market share [47,48]. The model runs in five-year time steps over the period 1990–2100, providing results for 32 distinct geopolitical regions (defined by colour in Fig. 1). By altering the fixed hydropower production inputs, the model is forced to adapt the power sector to ensure that power supply balances demand in each region. Power generating technologies that can be adopted include carbon-based fuels (conventional and integrated gasification combined cycle, with and without carbon capture and storage), renewables (geothermal, wind, and solar technologies) and nuclear facilities. The investment costs for these technologies (i.e., capital costs of plant installation) and their associated emissions (per unit energy produced) are tracked by the model.

The two scenarios explored in this study (RCP8.5 and RCP4.5) are developed to ensure consistency between GCAM and the hydropower impact model (Table 1). So for RCP8.5, GCAM is operated assuming a world in which carbon emissions are unconstrained—that is, there is no incentive to invest in low-carbon power generating technologies if conventional technologies are cheaper. Accordingly, hydropower generation projections are developed for this scenario by forcing the coupled hydrological and dam model with GCMs run under a relatively high emissions pathway (RCP 8.5). For the RCP 4.5 scenario, GCAM is operated assuming a global value for carbon emissions, which then guides the investment decisions consistent with limiting radiative forcing to no more than 4.5 W/m^2. Hydropower generation projections for this scenario are thus derived from GCMs run under RCP 4.5.

2.3. Impact assessment

To assess impacts, we concentrate on two output variables: CO_2 emissions from the power sector only (MTC/year) and cumulative investment in generating capacity discounted to the year 2010 (^{2010}$ billion). Each variable is determined for all 16 GCM realizations at both regional and global scales by computing absolute and percentage difference relative to a GCAM run in which hydropower availability is not affected by climate (i.e., the *no climate change* row in Table 1). Where climate change increases hydropower production (resulting in reduced emissions and less power sector investment relative to no climate change), the difference is referred to as *avoided* emissions or investments. Where climate change decreases hydropower production (resulting in increased emissions and more power sector investment relative to no climate change), the difference is referred to as *additional* emissions or investments.

Under RCP4.5, GCAM is operated to target a specific level of radiative forcing. This means that emissions are relatively insensitive to changes in input assumptions—the global value assigned to carbon will force the model to adapt by investing in technologies that limit radiative forcing to 4.5 W/m^2. Other sources of radiative forcing represented in GCAM include emissions from various sectors other than electricity production (industry, buildings, transport, etc.) as well as land use emissions. Therefore, even though the total radiative forcing will be insensitive to change in input hydropower assumptions for this scenario, variations in emissions specifically from the power sector are plausible, because changes in power sector emissions can be offset by changes in emissions from other sectors.

The experimental setup neglects all climate-influenced changes on electricity supply and demand not relating to hydropower (e.g., changes in cooling energy demand as temperatures increase, changes in thermal energy production caused water availability and temperature in rivers). Results thereby provide a clear indication of the contribution of hydropower gains and losses to the power sector emissions and investments, and should be interpreted as plausible projections of the impacts of climate change on these variables.

2.4. Investment risk

To assess investment risk for individual countries, we disaggregate regional cumulative power sector investment impacts. This is done by allocating the cumulative power sector investment

Table 1
Experimental set up. Unaffected hydropower (HP) expansion refers to hydropower expansion trajectories that neglect the possible effects of climate change on power generation.

		RCP8.5 scenario	RCP4.5 scenario
GCAM run mode		*Unconstrained*. Technological choices for expansion and replacement of power generating capacity are made independent of emissions impact.	*Targeted*: Technological choices for all sectors are resolved to ensure radiative forcing is limited to 4.5 W/m^2.
HP input	No climate change	Unaffected 21st century hydropower generation trajectories.	Unaffected 21st century hydropower generation trajectories.
	Climate change	Sixteen 21st century hydropower generation trajectories derived from GCMs run under RCP8.5.	Sixteen 21st century hydropower generation trajectories derived from GCMs run under RCP4.5.

impact (year 2100) to individual countries according to their (current) share of hydropower generation within the region. For example, in a region with two countries in which only one generates hydropower, all of the investment impact is assigned to that country. The formulation is:

$$X_{i,j} = X_j \times G_{i,j}/G_j$$

where $X_{i,j}$ is the 2100 cumulative investment impact (^{2010}\$ billion) and $G_{i,j}$ is current observed hydropower generation [49] for country i, belonging to region j. X_j and G_j are total 2100 cumulative investment impact and total current observed hydropower generation for region j (^{2010}\$ billion), respectively. Since a country's vulnerability to each dollar of additional investment would vary depending on the size of its economy, we divide impact on investment by Gross Domestic Product to give a crude risk score that can be used to identify countries most likely to be impacted by climate-driven losses and gains in hydropower production. This *Investment Risk Score* (%) is computed as the 2100 cumulative investment impact as a percentage of current (annual) GDP.

$$Investment\ Risk\ Score_i = X_i/GDP_i \times 100$$

3. Results and discussion

3.1. Climate change impacts on 21st century hydropower production

We project a change in net global hydropower production of between −8% and +5% under RCP8.5 and between −4% and +4% under RCP 4.5 by the end of the century depending on GCM (Table 2). Power production is reduced at the majority of modelled dams under either emissions scenario (only one of sixteen GCMs counters this finding). These results are similar to findings of prior studies, although we find that when averaged across all GCMs, the net reduction in hydropower generation is slightly less than found in Ref. [16] (for which the RCP8.5 results should be directly comparable). The observed discrepancy between studies is likely to be consequence of both the dam model and the number of GCMs considered. Differences between our findings for the 2080s time slice and that of [15]—which applied the same dam model—reflect known differences in strength of emissions forcing between the CMIP-3 and CMIP-5 emissions scenarios (described in Ref. [50].

Whilst climate change is projected to manifest in a modest increase in mean net global precipitation of approximately 2% per degree of warming [51], specific regions are projected to experience a much stronger signal of wetting or drying. The weak globally aggregated impacts described above therefore mask much stronger regional impacts (Fig. 2). Generally, the magnitudes and uncertainties of regional impacts are greater for the baseline (RCP8.5) scenario than for the RCP4.5 scenario. A mixture of gains and losses in hydropower generation (relative to no climate change) is evident across the different regions, although percentage losses (such as in Argentina) tend to exceed percentage gains (such as in Russia). This behavior is caused partly by the non-linearity in hydropower generation response to climate change. Hydropower production will fail to increase linearly with flow in instances where plants are already operated at maximum capacity (i.e., consistently high hydraulic head and maximum turbine release rates reached). In regions experiencing reduced flows, hydropower production will tend to suffer dual impacts of lost inflows and increased evaporation losses from the reservoir surface. So the negative impacts incurred in drier regions tend to be more pronounced than the positive impacts incurred in wetter regions (which may also partially explain why the net global effect is a reduction in hydropower generation despite a net increase in precipitation projected globally). Regions that suffer substantial loss in hydropower generation and for which hydropower contributes a significant proportion of total power generation include Europe (non-EU) and the Latin American regions of northern South America and Argentina. Hydropower-reliant regions that benefit from substantial gains in hydropower generation include East Africa, Canada, the European Free Trade Agreement countries, Russia, South Asia, and Southeast Asia. Hydropower also contributes significantly to power production in southern South America, Colombia, Brazil, Central Asia, China, Pakistan, and the United States—regions for which there is a lack of GCM agreement on the direction of impact.

3.2. Impacts on power sector emissions and investments

Fig. 3 displays projected net global impacts on both power sector emissions and investment costs for all GCMs. The range of results for net global impact across GCMs reflects the uncertainty in global hydropower production discussed above. The uncertainty is a direct result of GCM disagreement on how water will be distributed throughout the world in the 21st century. GCMs that distribute more water to major hydropower generating basins will likely produce results suggesting increased hydropower production and therefore fewer investments in new capacity and lower net emissions. Conversely, GCMs that distribute less water to major hydropower generating basins will likely produce the opposite effect—increased investment requirements and/or higher net emissions. GCM disagreement as to which of these realizations will dominate means that it remains unclear whether climate change will imply a net global increase or net global decrease in either of the two variables considered. Nonetheless, the magnitude of the net global impacts is modest. Even under RCP8.5 and assuming the most extreme GCMs, the relative impact of climate change on either variable is less than 0.5% compared to the GCAM assessment that neglects climate impacts on hydropower. A change of 0.5% in power sector CO_2 emissions amounts to a negligible potential impact on total global greenhouse gas emissions, and so the threat of a

Table 2
Comparison of globally aggregated projections between this study and two prior top down assessments of climate change impacts on global hydropower production. Impacts are based on mean across GCMs.

		van Vliet et al. [16]		Turner et al. [15]		This study	
		RCP8.5	*RCP2.6*	*SRES A2*	*SRES B1*	*RCP8.5*	*RCP4.5*
Global impact (% diff. from 1965 to 2000)	2010–39	−1.9	−1.7	−1.6	−1.3	−0.9	−0.4
	2040–69	−3.6	−1.2	−1.5	−1.3	−1.2	−0.6
	2070–99	−6.1	−0.4	−1.0	−0.4	−2.2	−0.5
% of plants w/less production (2050s)		74	61	66	61	60	57
GCMs		5 × CMIP-5 GCMs (ISI-MIP)		3 × CMIP-3 GCMs (WATCH)	3 × CMIP-3 GCMs (WATCH)	16 × CMIP-5 GCMs (Reclamation)	16 × CMIP-5 GCMs (Reclamation)
GHM		VIC		WaterGAP		GWAM	
Flow routing		DDM30		DDM30		Modified RTM	
Dam model		Static: hydropower computed directly from flow.		Dynamic: hydropower computed using simulated reservoir storage flux (dynamic storage, head levels and wet surface area).			
Hydropower dams modelled		24,515 (78% global installed capacity)		1593 (54% global installed capacity)			

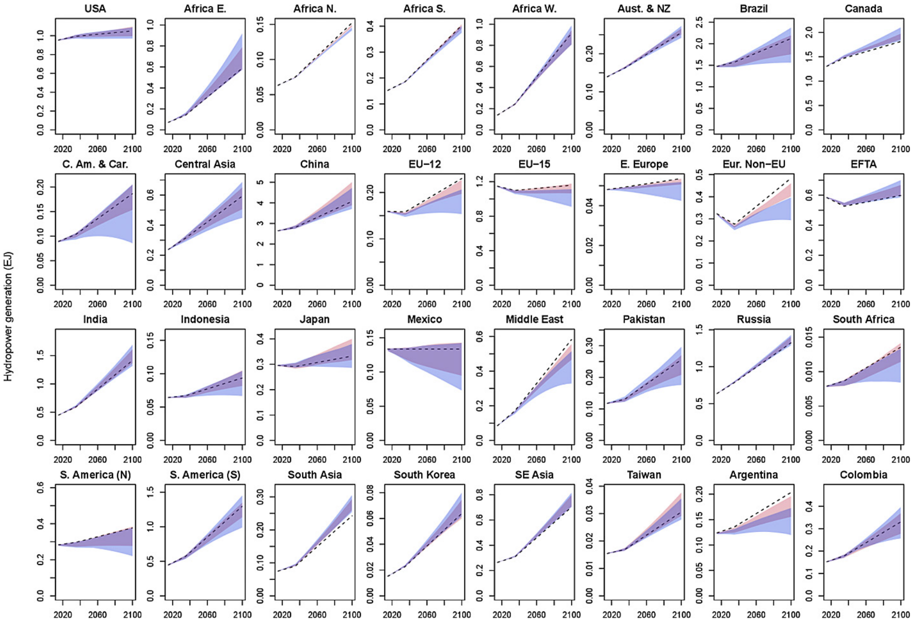

Fig. 2. Hydropower expansion projections for all GCAM regions. Dashed line gives baseline (no climate change) projection, whilst blue and red cones give uncertainty (10th − 90th percentiles) across sixteen GCMs for RCP 8.5 and RCP 4.5 emissions respectively.

reinforcing feedback loop acting to exacerbate climate change (i.e., dominance of the dry feedback loop depicted to the left of the charts in Fig. 3) can be safely discarded.

For the RCP4.5 scenario, the impacts on power sector emissions are an order of magnitude less and can be considered negligible (Fig. 3b). This result is unsurprising, because under RCP4.5 GCAM is operated to constrain radiative forcing to a pre-specified level irrespective of the input assumptions. In other words, whilst there may be significant impacts on the power sector under RCP4.5, these will be evident through its technological composition, which is adapted to meet the demand for power whilst limiting its contribution to radiative forcing. We therefore look to the power sector investment costs to understand impacts under RCP4.5.

Emissions scenario choice has relatively little effect on cumulative investment cost impacts at the global aggregated level for the majority of GCMs (Fig. 3c and d). For some GCMs (e.g., CESM1-CAM5) the net impact is actually greater under RCP4.5 than under RCP8.5. This is an interesting result, because one might expect the more severe climate impacts associated with RCP8.5 to cause greater impacts on investments as more hydropower generating capability is lost or gained. The reason we get this result is that total power sector investment costs are the product of both the required generating capacity and the marginal cost of installing that capacity—which depends on the technologies being deployed. Under RCP4.5, GCAM is more likely to adopt expensive, low carbon technology options to meet the constraint on radiative forcing. Absent of this constraint (as in RCP8.5) GCAM will tend to adopt inexpensive, carbon-intensive technologies. This behavior is shown clearly in Fig. 4a, which compares across the two scenarios the sensitivity of generation from conventional coal in response to changes in hydropower. Coal is both inexpensive and carbon intensive relative to other technologies. This contrasts with Fig. 4b, which tracks the sensitivity of generation from low carbon technologies in response to changes in hydropower. These technologies are more expensive, comprising nuclear as well fossil generation with carbon capture and storage. In other words, changes in hydropower under RCP8.5 are balanced by addition or retirement of relatively inexpensive technologies, whilst changes in hydropower

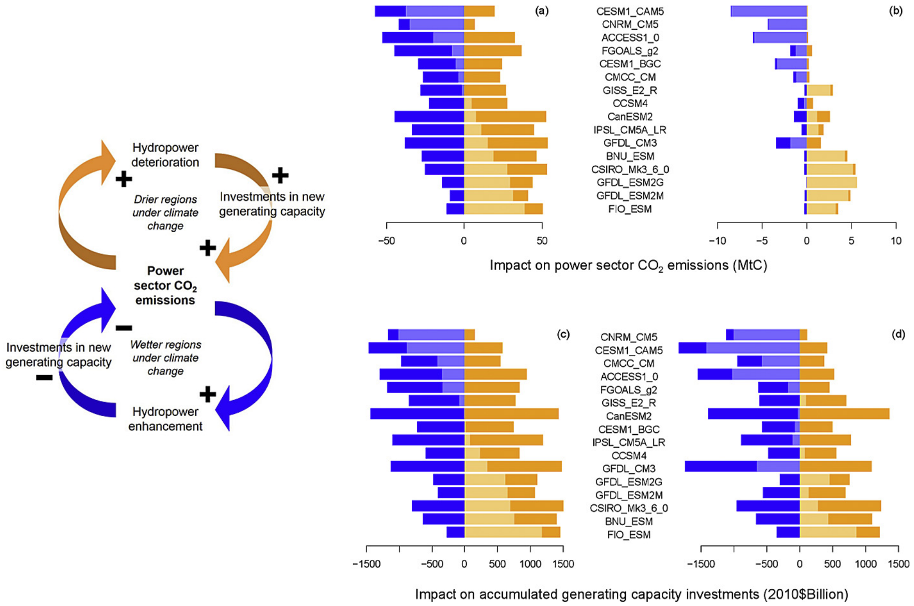

Fig. 3. Net global impacts of climate change on year 2100 CO_2 emissions (a – RCP8.5, b – RCP4.5) and accumulated power sector investments (c – RCP8.5, d – RCP4.5). Blue bars give net impact from regions that benefit from emissions/investment avoided whist orange bars give net impact from regions that suffer emissions/investment added. Internal transparent bars give overall net global impact. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

under RCP4.5 are balanced by addition or retirement of relatively expensive technologies. The marginal cost of power generation is greater under RCP4.5—which explains why the net investment costs are comparable to RCP8.5 even though the impacts on hydropower are less severe.

Regional impacts (year 2100) on hydropower and consequent impacts on emissions and cumulative investment costs are displayed in Table 3. For any given region, three factors determine the level of impact on emissions or investments: the impact of climate change on hydropower generation (given on the left of the table), the importance of hydropower relative to other technologies (e.g., percentage of power demand met by hydropower), and the type of technologies that are retired or adopted to balance electricity supply and demand. Whilst impacts on emissions are modest and ambiguous at the global level (discussed above), many regions are projected to experience significant impacts on emissions under RCP8.5. Substantial climate impacts on emissions of 15–20% are evident in Latin American regions, for example. In regions where hydropower production is enhanced, the avoidance of adopting emitting technologies will result in a reduction in emissions relative to no climate change. There is strong model agreement that Canada and the European Free Trade Agreement (EFTA) region would reap this benefit under RCP8.5. For investment impacts, we see again the pattern observed at the global level, where the impacts for RCP8.5 are broadly in agreement with RCP4.5. One exception to this rule is China, for which the impact on cumulative investment for RCP4.5 (mean impact across all GCMs) is more than double the impact for RCP8.5. This result reflects the odd situation in China where the mean impact on hydropower across the GCM ensemble is actually more severe under RCP4.5 than

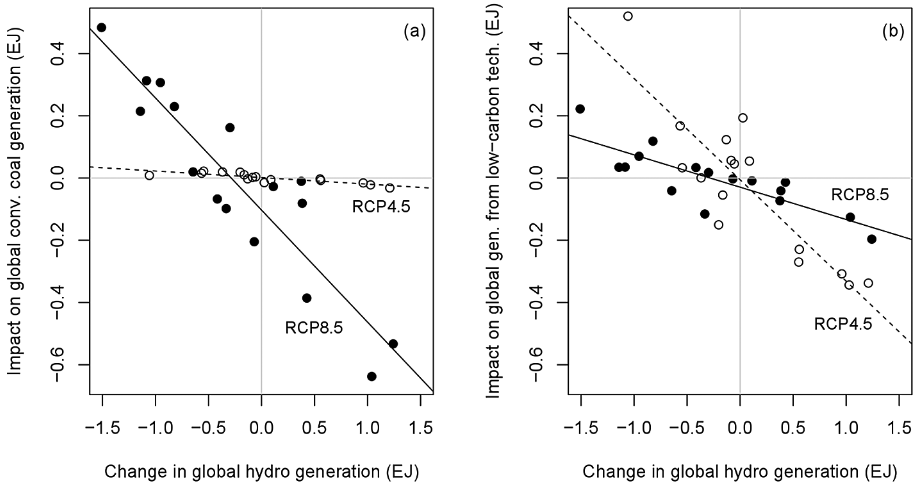

Fig. 4. GCAM response to change in hydropower generation across sixteen GCMs for (a) conventional coal generation, and (b) generation from a selection of comparatively expensive, low carbon technologies (specifically, fossil sources with carbon capture and storage, and nuclear). Results are for year 2100. Filled circles and solid, linear trend line give RCP8.5 results whilst unfilled circles and broken, linear trend line give RCP4.5.

Table 3
Year 2100 regionally aggregated impacts (absolute and percentage) of climate change on hydropower production and consequent impacts on power sector emissions and cumulative investment costs (RCP4.5 and RCP8.5 scenarios). The sixteen-member GCM ensemble is used to compute mean and standard deviation of impact. Impact is relative to a GCAM run that neglects climate change effects on hydropower.

Region	Impact on hydropower				Impact on power sector CO_2 emissions								Impact on cumulative power sector investments (discounted to 2010)							
	RCP8.5		RCP4.5		RCP8.5				RCP4.5				RCP8.5				RCP4.5			
	(mean)		(mean)		(mean)		*(st. dev.)*		(mean)		*(st. dev.)*		(mean)		*(st. dev.)*		(mean)		*(st. dev.)*	
	ExaJ	%	ExaJ	%	MTC	%	*MTC*	*%*	MTC	%	*MTC*	*%*	$bill.	%	*$bill.*	*%*	$bill.	%	*$bill.*	*%*
Africa E.	0.13	21.8	0.07	12.5	−2.79	−1.07	*3.00*	*1.14*	−0.08	−0.63	*0.15*	*1.10*	−71.2	−0.49	*82.5*	*0.56*	−72.6	−0.34	*93.4*	*0.44*
Africa N.	−0.01	−5.6	0.00	−2.7	0.17	0.13	*0.05*	*0.04*	0.01	0.09	*0.12*	*0.95*	4.1	0.07	*1.2*	*0.02*	2.7	0.03	*1.8*	*0.02*
Africa S.	−0.01	−3.6	−0.01	−1.5	0.52	0.13	*0.53*	*0.13*	0.02	0.08	*0.22*	*0.90*	7.4	0.09	*7.8*	*0.10*	4.4	0.03	*8.2*	*0.07*
Africa W.	−0.03	−3.1	−0.03	−2.8	0.56	0.09	*1.68*	*0.27*	0.07	0.12	*0.65*	*1.04*	11.8	0.07	*30.5*	*0.17*	13.4	0.04	*33.9*	*0.10*
Argentina	−0.06	−27.5	−0.03	−13.3	1.02	3.87	*0.44*	*1.67*	0.03	1.48	*0.02*	*0.98*	30.5	2.25	*13.4*	*0.99*	22.7	1.13	*13.5*	*0.67*
Austr./NZ	0.00	0.2	0.00	1.4	−0.02	−0.02	*0.43*	*0.50*	−0.01	−0.13	*0.01*	*0.31*	−0.5	−0.01	*10.2*	*0.27*	−3.7	−0.08	*7.3*	*0.15*
Brazil	−0.11	−5.2	−0.12	−5.8	2.97	2.23	*8.47*	*6.35*	0.22	2.13	*0.34*	*3.31*	81.9	1.49	*213.0*	*3.87*	115.4	1.49	*189.9*	*2.45*
Canada	0.18	9.8	0.10	5.6	−3.19	−5.84	*2.16*	*3.96*	−0.07	−2.31	*0.04*	*1.21*	−195	−3.82	*121.2*	*2.38*	−145	−2.10	*68.0*	*0.98*
C. Am/Car.	−0.04	−22.2	−0.02	−8.1	0.90	1.29	*1.09*	*1.55*	0.02	0.46	*0.04*	*0.91*	30.5	0.75	*36.4*	*0.89*	15.7	0.28	*26.0*	*0.46*
Central Asia	−0.02	−3.4	0.00	0.1	0.39	1.10	*2.01*	*5.68*	0.00	−0.03	*0.05*	*1.78*	11.1	0.38	*76.2*	*2.61*	−4.1	−0.09	*54.9*	*1.24*
China	0.14	3.5	0.21	5.2	−4.94	−0.71	*16.07*	*2.31*	−0.26	−0.73	*0.61*	*1.69*	−89.7	−0.17	*423.6*	*0.79*	−229	−0.33	*509.1*	*0.74*
Colombia	−0.01	−1.7	−0.01	−3.9	0.16	0.46	*2.07*	*6.08*	0.02	0.83	*0.09*	*3.06*	3.9	0.40	*41.1*	*4.13*	8.9	0.60	*35.1*	*2.38*
EU-12	−0.05	−20.8	−0.02	−7.7	1.55	1.54	*0.70*	*0.70*	0.02	0.39	*0.02*	*0.54*	39.4	0.65	*18.5*	*0.30*	20.6	0.28	*12.4*	*0.17*
EU-15	−0.16	−13.9	−0.04	−3.9	3.11	0.88	*1.54*	*0.43*	0.03	0.19	*0.10*	*0.73*	153.5	0.47	*83.2*	*0.25*	67.7	0.17	*65.3*	*0.16*
Europe E.	−0.01	−9.8	0.00	−3.3	0.09	0.35	*0.06*	*0.25*	0.00	0.07	*0.00*	*0.32*	5.6	0.20	*4.1*	*0.15*	2.5	0.07	*2.1*	*0.06*
Eur. ex. EU	−0.14	−28.1	−0.06	−12.1	4.13	4.36	*1.48*	*1.57*	0.08	1.52	*0.06*	*1.22*	95.5	2.40	*35.5*	*0.89*	56.5	1.09	*30.9*	*0.59*
EFTA	0.04	6.6	0.03	5.1	−0.47	−5.12	*0.52*	*5.65*	−0.02	−2.95	*0.02*	*2.79*	−44.5	−3.25	*43.4*	*3.17*	−40.1	−2.36	*35.9*	*2.11*
India	0.10	7.3	0.08	6.0	−4.17	−0.22	*7.36*	*0.38*	−0.16	−0.17	*0.98*	*1.06*	−71.3	−0.12	*120.4*	*0.20*	−75.6	−0.09	*100.3*	*0.11*
Indonesia	0.00	0.8	0.00	0.9	−0.03	−0.01	*0.86*	*0.42*	0.00	0.00	*0.13*	*1.17*	0.3	0.00	*15.5*	*0.23*	0.3	0.00	*12.6*	*0.13*
Japan	0.01	2.0	0.02	6.6	−0.18	−0.21	*1.14*	*1.28*	−0.03	−0.49	*0.05*	*0.89*	−9.0	−0.13	*33.2*	*0.47*	−22.6	−0.26	*34.7*	*0.40*
Mexico	−0.03	−23.6	−0.02	−11.3	0.82	0.66	*0.86*	*0.69*	0.03	0.31	*0.07*	*0.69*	18.0	0.40	*18.8*	*0.42*	13.4	0.21	*18.3*	*0.29*
Middle East	−0.15	−25.4	−0.08	−14.2	3.30	1.02	*1.93*	*0.60*	0.15	0.48	*0.18*	*0.59*	55.0	0.42	*33.6*	*0.26*	52.8	0.25	*29.1*	*0.14*
Pakistan	−0.01	−3.0	−0.02	−6.1	0.17	0.11	*1.11*	*0.75*	0.03	0.29	*0.12*	*1.19*	5.5	0.07	*35.8*	*0.48*	14.8	0.13	*24.5*	*0.22*
Russia	0.03	2.6	0.03	2.4	−0.53	−0.72	*0.95*	*1.27*	−0.02	−0.42	*0.03*	*0.59*	−31.6	−0.38	*48.7*	*0.59*	−34.9	−0.29	*43.3*	*0.36*
South Africa	0.00	−17.4	0.00	−7.5	0.10	0.10	*0.09*	*0.10*	0.00	0.07	*0.03*	*0.95*	1.9	0.05	*1.9*	*0.05*	1.2	0.02	*1.5*	*0.03*
S. Am. (N)	−0.07	−17.3	−0.05	−12.4	1.34	5.58	*1.97*	*8.21*	0.06	3.37	*0.07*	*3.87*	54.9	3.28	*76.2*	*4.56*	55.0	2.30	*61.8*	*2.58*
S. Am. (S)	−0.05	−4.2	−0.06	−4.4	1.48	2.10	*4.85*	*6.88*	0.09	2.06	*0.16*	*3.56*	29.7	1.13	*96.3*	*3.65*	39.4	1.17	*72.7*	*2.16*
South Asia	0.04	15.3	0.03	12.7	−0.72	−0.51	*0.40*	*0.29*	−0.06	−0.50	*0.15*	*1.31*	−17.7	−0.35	*10.2*	*0.20*	−21.1	−0.28	*13.4*	*0.17*
South Korea	0.01	10.7	0.00	6.8	−0.19	−0.43	*0.20*	*0.47*	0.00	−0.20	*0.02*	*1.42*	−5.3	−0.12	*5.4*	*0.12*	−4.4	−0.08	*5.4*	*0.10*
S.E. Asia	0.05	7.8	0.04	6.0	−1.59	−0.47	*1.42*	*0.42*	−0.09	−0.31	*0.22*	*0.76*	−29.2	−0.26	*25.1*	*0.22*	−31.5	−0.20	*26.5*	*0.17*
Taiwan	0.00	3.5	0.00	5.2	−0.04	−0.09	*0.13*	*0.27*	0.00	−0.08	*0.06*	*1.37*	−0.6	−0.03	*2.4*	*0.11*	−1.5	−0.05	*3.0*	*0.10*
USA	−0.02	−1.7	−0.01	−0.5	0.59	0.07	*1.58*	*0.19*	0.01	0.01	*0.14*	*0.30*	16.2	0.04	*50.1*	*0.11*	5.9	0.01	*45.8*	*0.08*

RCP8.5—investments are not only more expensive, but more power generating capacity is required to balance supply and demand.

Substantial cumulative investment cost impacts of more than $100 billion are projected for most studied regions by 2100 under the most extreme climate realizations (note: all investment impacts given in 2010 dollars). In China, avoided investment costs exceed $1 trillion for some GCM projections. Canada may avoid up to $300 billion. On the flipside, many regions, particularly those located in Latin America as well as Europe and the Middle East, are projected to face additional power sector investment costs in the order of $50–100billion by 2100, caused by deteriorated hydropower generation under climate change. The substantial uncertainty in hydropower production across the GCM projections (Fig. 2) is reflected in many of the regional impacts. In Brazil, for example, the mean of the GCM ensemble indicates a net increase in required investments of approximately ^{2010}$100billion for both RCP8.5 and RCP4.5. But the standard deviation of this impact across the GCM ensemble is in the order of ^{2010}$200billion, highlighting enormous uncertainty of economic impact for a country that relies on hydropower to provide roughly three quarters of its power supply.

3.3. Country-level investment risk

The purpose of our risk analysis is to determine whether the investment cost impacts reported above represent a significant threat or opportunity for individual countries. Fig. 5 maps Investment Risk Scores (Section 2.3) for all countries (based on cumulative investment for 2100 under RCP 4.5). The map highlights a lopsided distribution of risk and opportunity in which the vast majority of countries are relatively unaffected ($-0.01 \leq$ IRS $\leq +0.01$%). The small selection of heavily affected countries generally have at least three of four common traits: high impact of climate change on hydrology; strong GCM agreement in direction of impact; high reliance on hydropower to meet electricity demands; and relatively low GDP. Some countries where GCM agreement is poor are still classified as high risk if GDP is small relative to implied costs (primarily countries in Africa). Paraguay is classified as the highest risk country according to the Investment Risk Score, despite large uncertainty in the direction of impact. Paraguay's expected (mean) impact is $17 billion (additional) by 2100—but estimates range from $69 billion avoided to $174 billion additional depending on GCM. Whether these numbers should be deemed important or not depends on perspective. A sum of $174 billion would represent a minute fraction of Paraguay's GDP, but would surely constitute a substantial portion of power sector investment costs. Whilst the magnitude of these costs may warrant their inclusion in country-wide energy strategy, the inherent uncertainty would present significant problems for planners seeking consensus on how to invest to secure electricity supplies in these growth regions.

Strong GCM agreement (defined here as at least fourteen of sixteen GCMs projecting hydropower impacts in the same

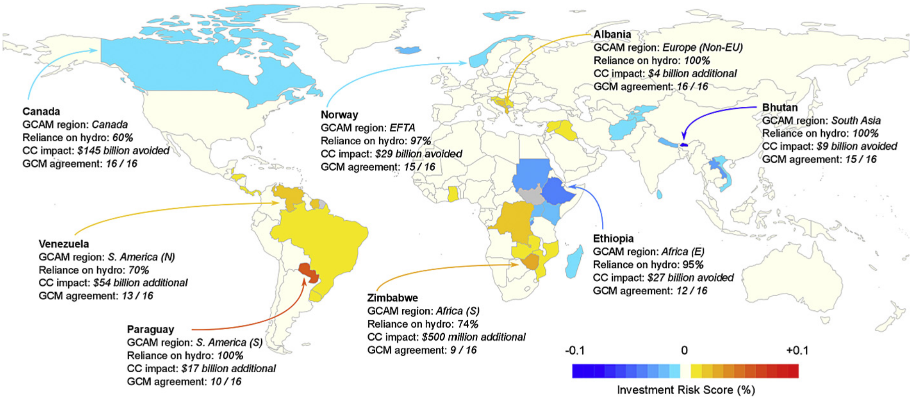

Fig. 5. Map of GCAM regions coloured by Investment Risk Score. For captions: *reliance on hydro* gives percentage of total power generation from hydro (as measured 2008–2012); *CC impact* gives impact on accumulated investment (year 2100, RCP4.5 scenario); and GCM agreement specifies proportion of GCMs that agree on the direction of impact (i.e., investment avoided or additional investment) for the relevant GCAM region. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

direction) is found for eight of 32 regions under the RCP 4.5 scenario. Of these eight regions, only four contain countries that rely heavily on hydropower to meet power demands. These are Europe non-EU (unanimous GCM agreement), Canada (unanimous), South Asia (15/16) and Southeast Asia (15/16). Europe non-EU is made up predominantly of the Balkans countries, some of which have been previously identified as potential vulnerability hotspots [15]. The most heavily impacted of these will be Montenegro, Albania, and Bosnia and Herzegovina. Under the worst case scenario, the additional cumulative investment requirement for the Balkans region as a whole amounts to $68 billion by 2100. A further $81 billion would be required in Turkey (also Europe non–EU) under this extreme case. Bhutan (South Asia GCAM region) gets a higher absolute Investment Risk Score than any other country. Here the impact is considered an opportunity rather than a risk, as fifteen of sixteen GCMs indicate significant cost avoided (expected saving = $9 billion by 2100). Other countries likely to benefit significantly from increased hydropower production include Canada ($145 billion expected costs avoided) and Norway ($29 billion). Results for all countries with estimated Investment Risk Scores greater than 0.05% are displayed in Table 4.

It is important to note that some large countries may contain within them sub-regions that are likely to experience much greater impact than is projected for the country as a whole. For example, high risk power networks located in southwestern United States (where impacts may look something closer to Mexico) could be overlooked due to balancing of increased generation in northern United States (where impacts may look something more like Canada – see Fig. 2). A detailed study focused on individual power grids would provide a much more comprehensive assessment of global vulnerability to climate change, but lies beyond the scope of the present work.

4. Conclusions

This study combines a global hydrological and dam model with an integrated assessment model to assess impacts of climate change on power sector technological composition and associated impacts. The approach is state-of-the-art in at least three respects: application of fine detailed dam model that captures nonlinearity in hydropower generation response to climate change; use of a comprehensive suite of input climate realizations from sixteen CMIP-5 GCMs; and inclusion of feedback between the operating mode incorporated in the integrated assessment model and the emissions scenario assumed in climate projections used to drive the global hydropower model.

At the aggregate global level, the implications of climate-driven losses and gains in hydropower production on emissions are generally modest, and with an ambiguous sign (±0.5% impact on power sector CO_2 emissions by the end of the century under RCP8.5). This global impact masks more significant impacts at the regional level. For certain regions—specifically those in which climate impacts on hydrology are severe and for which hydropower meets a large proportion of electrical power demand—some GCMs project impacts on power sector emissions of 15–20% by the end of the century. Climate-driven losses in hydropower generation must be substituted by increased investment in alternative means of power generation. We find that this risk is present and is of similar severity irrespective of the emissions scenario considered. Absent efforts to constrain emissions, climate impacts on hydropower generation are more severe, resulting in greater replacement requirements and associated investment. On the other hand, if measures are taken to constrain emissions, impacts on hydropower generation are moderated substantially, but not sufficiently to compensate for the increasing costs of additional capacity when a global value on carbon is adopted.

When investment costs are disaggregated to country level and presented as a fraction of gross domestic product, a small selection of vulnerable countries emerge. These countries are characterized by heavy reliance on hydropower to meet current power demands and strong confidence in the direction of climate change. A number of developing countries in Latin American, Southern Africa, and the Balkans may face additional cumulative investment costs in the order of tens of billions of dollars by the end of the century to substitute for lost hydropower generating capacity. These impacts are non-trivial given the limited ability of developing nations to raise finance for power sector projects. Any new investments in power plants would also imply various social and environmental costs associated with infrastructure development that are neglected in the present work. Regions that stand to lose power generation from existing hydropower facilities will have to make up the shortfall by shouldering the spectrum of costs associated with expansion of alternative technologies—not just financial investment.

Further analysis might incorporate a range of different mechanisms through which climate change could affect the power sector (see Ref. [52]. The science community has developed various tools for assessing global and regional climate impacts on electricity

Table 4
Disaggregated, country-level climate change impacts on power sector investments (year 2100 cumulative, RCP 4.5 scenario) and associated Investment Risk Scores based on expected cost impact. Expected, best case, and worst case cost impacts are based on mean, minimum and maximum of sixteen GCMs respectively.

Country	GCAM region	Share of hydro within region (%)	Investment cost impact (^{2010}$ billion)			*Investment Risk Score (%)*
			Expected	Best case	Worst case	
Bhutan	S Asia	42.3	−8.9	−22.6	3.9	*−0.254*
Paraguay	S America (S)	44.6	17.6	−30.6	77.6	*0.061*
Ethiopia	Africa East	36.9	−26.8	−103.7	12.1	*−0.039*
Laos	SE Asia	13.7	−4.3	−13.3	0.8	*−0.031*
Sudan	Africa E	35.7	−26.0	−100.6	11.7	*−0.029*
Burundi	Africa E	1.2	−0.9	−3.4	0.4	*−0.028*
Zimbabwe	Africa S	11.4	0.5	−0.6	3.3	*0.026*
Iceland	EFTA	6.9	−2.8	−8.0	0.8	*−0.022*
Suriname	S America (N)	1.5	0.8	−1.0	3.2	*0.020*
Montenegro	Europe (non EU)	2.4	1.3	0.3	3.5	*0.019*
D Rep. Congo	Africa W	26.1	3.5	−8.3	25.7	*0.017*
Albania	Europe (non EU)	6.4	3.6	0.9	9.6	*0.017*
Kenya	Africa East	13.3	−9.6	−37.3	4.4	*−0.016*
Bosnia & Herz.	Europe (non EU)	8.0	4.5	1.1	11.9	*0.015*
Venezuela	S America (N)	98.0	53.9	−63.6	207.0	*0.015*
Nepal	South Asia	22.2	−4.7	−11.8	2.1	*−0.015*
Uganda	Africa East	8.1	−5.9	−22.9	2.7	*−0.015*
Madagascar	Africa East	3.4	−2.5	−9.6	1.1	*−0.012*
Canada	Canada	100.0	−145.1	−311.6	−58.4	*−0.011*
Norway	EFTA	72.9	−29.2	−85.1	8.8	*−0.011*
Serbia	Europe (non EU)	15.0	8.5	2.0	22.4	*0.011*
Ghana	Africa W	24.9	3.3	−7.9	24.4	*0.010*
Costa Rica	C Am & Car.	28.8	4.5	−6.6	23.4	*0.009*
Panama	C Am & Car.	21.6	3.4	−4.9	17.5	*0.009*
Croatia	Europe (non EU)	12.1	6.8	1.6	18.1	*0.008*
Tajikistan	Central Asia	26.2	−1.1	−18.9	29.0	*−0.008*
Mozambique	Africa S	33.9	1.5	−1.8	9.8	*0.008*
Syria	Middle East	14.5	7.7	2.0	18.5	*0.008*
Kyrgyzstan	Central Asia	21.8	−0.9	−15.7	24.1	*−0.008*
Rwanda	Africa East	1.0	−0.7	−2.8	0.3	*−0.008*
Zambia	Africa S	29.4	1.3	−1.6	8.5	*0.007*
Iraq	Middle East	14.2	7.5	1.9	18.1	*0.007*
Uruguay	S. America (S)	7.8	3.1	−5.3	13.5	*0.007*
Belize	C Am & Car.	1.1	0.2	−0.3	0.9	*0.007*
Vietnam	SE Asia	49.6	−15.6	−48.3	3.1	*−0.006*
Sri Lanka	South Asia	26.7	−5.6	−14.2	2.5	*−0.006*
Brazil	Brazil	100.0	115.4	−146.0	507.1	*0.006*
Slovenia	EU-12	15.0	3.1	−0.2	6.6	*0.005*
Honduras	C Am & Car.	11.2	1.7	−2.5	9.1	*0.005*
Afghanistan	South Asia	5.3	−1.1	−2.8	0.5	*−0.005*

supply (e.g., impacts on thermal cooling: [16,53] and demand (e.g., building cooling and heating loads: [2,54]. Combining all these impacts into unifying climate risk assessment for the power sector would provide timely evidence to support the planning of next generation infrastructure.

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