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Power-generation system vulnerability and adaptation to changes in climate and water resources

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Hydropower and thermoelectric power together contribute 98% of the world's electricity generation at present[1]. These power-generating technologies both strongly depend on water availability, and water temperature for cooling also plays a critical role for thermoelectric power generation. Climate change and resulting changes in water resources will therefore affect power generation while energy demands continue to increase with economic development and a growing world population. Here we present a global assessment of the vulnerability of the world's current hydropower and thermoelectric power-generation system to changing climate and water resources, and test adaptation options for sustainable water–energy security during the twenty-first century. Using a coupled hydrological–electricity modelling framework with data on 24,515 hydropower and 1,427 thermoelectric power plants, we show reductions in usable capacity for 61–74% of the hydropower plants and 81–86% of the thermoelectric power plants worldwide for 2040–2069. However, adaptation options such as increased plant efficiencies, replacement of cooling system types and fuel switches are effective alternatives to reduce the assessed vulnerability to changing climate and freshwater resources. Transitions in the electricity sector with a stronger focus on adaptation, in addition to mitigation, are thus highly recommended to sustain water–energy security in the coming decades.

The world's electricity sector strongly depends on the availability and temperature of water resources for hydropower generation and for cooling of thermoelectric (nuclear, fossil-fuelled, biomass-fuelled and geothermal) power. In 2010, thermoelectric power contributed 16,473 million MWh (81%) of current electricity generation worldwide and hydropower 3,402 million MWh (17%; ref. 1) (Fig. 1). In most regions, thermoelectric power is the dominant power-generating technology, except in South America, where hydropower dominates (63% of total electricity generation). Although solar photovoltaics and wind power are growing rapidly, several scenario studies show that thermoelectric power, together with hydropower, will most likely remain the dominant power-generating technologies during the whole of the twenty-first century[2,3].

Previous studies showed that global warming, with increased climate variability and likelihoods of heat waves and droughts[4,5], may have important impacts on water resources available for hydropower[6,7] and thermoelectric power generation[8,9]. These climate change-induced alterations in water resources will therefore directly impact the interdependence of water and energy, commonly called the 'water–energy nexus'[10,11]. In addition, the demands for electricity are expected to increase under a growing world population with changing consumption patterns[2,12]. According to ref. 13 global water consumption for power generation is projected to double within the next four decades, increasing the scarcity and competition for water across sectors (for example, agriculture, energy, domestic). A better understanding of the extent of water constraints on electricity production and the options for improving water–energy security are needed for planning purposes, as are enhanced tools and methods to perform such assessments.

Although integrated assessment models are powerful tools for large-scale energy studies, most of these models provide output at coarse spatial and temporal resolutions[14]. Coupled hydrological–electricity modelling approaches include detailed processes that incorporate the impacts of regional or local water constraints on power supply, but limited work has been done, in particular at the large scale. Most coupled water–energy studies focus on the local or country level[15–17]. However, large-scale studies are needed for consistent comparisons of the linkages between climate change, changing water resources and electricity supply, and to identify critical focus regions. Here we quantify how future changes in global freshwater resources will affect water-dependent electricity supply during the twenty-first century using a coupled hydrological–electricity modelling approach. In addition, we test various adaptation options to mitigate the vulnerability of the world's electricity sector to water constraints under changing climate.

We developed a global hydrological–electricity modelling framework consisting of a physically based hydrological[18] and water temperature model[19,20], which were linked to hydropower and thermoelectric power models[9,21] (Supplementary Section 1). The modelling framework focuses on the physical impacts of water constraints on current power plant capacities. Economic feedbacks of the assessed water constraints and related adaptation options (for example, on energy prices, supply–demands portfolio) are not modelled. The modelling framework was applied to 24,515 hydropower plants and 1,427 thermoelectric power plants worldwide, which together contribute 78% of the total hydropower installed capacity and 28% of the thermoelectric power installed capacity worldwide. Thermoelectric power plants could be considered only if cooling system type was reported and river water was used for cooling. The spatial distribution and main characteristics of selected power plants are representative for the full power plant portfolio (Supplementary Section 2). We evaluated the modelling framework using observed records of streamflow, water temperature, hydropower and thermoelectric power generation, which showed an overall realistic representation of the observed conditions (Supplementary Section 3). We then forced the modelling framework with bias-corrected[22] general circulation models (GCMs) output from five GCMs and

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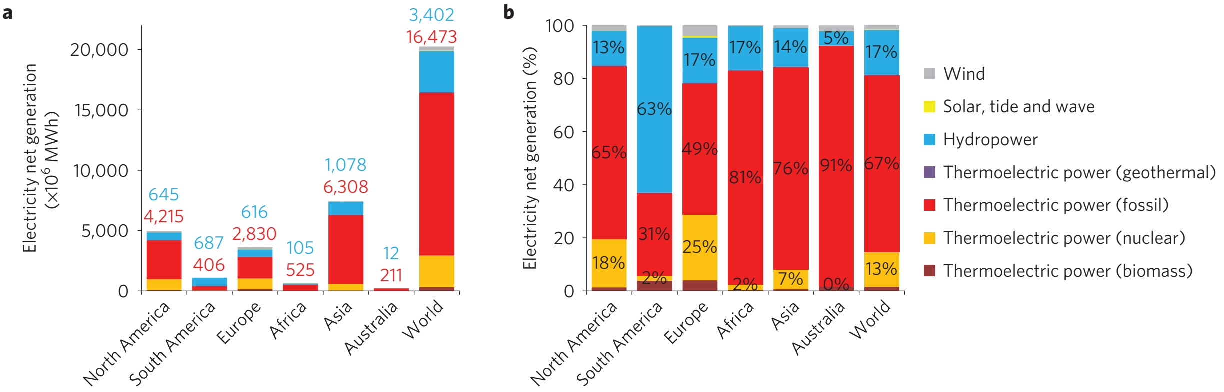

Figure 1 | Contribution of hydropower and thermoelectric power to total electricity generation in different regions worldwide. a,**b**, Absolute values (in 10^6 MWh; **a**) and the relative contribution (%; **b**) of hydropower (blue) and total thermoelectric (fossil, nuclear, biomass and geothermal) (red) calculated on the basis of data from the US Energy Information Administration[1] for the year 2010.

for the representative concentration pathways (RCPs) 2.6 (ref. 23) and 8.5 (ref. 24) for 1971–2099 (Supplementary Section 4). Impacts of changing climate and water resources on thermoelectric and hydropower usable capacity were quantified for 2010–2039 (2020s), 2040–2069 (2050s) and 2070–2099 (2080s) relative to the control period 1971–2000. To account for uncertainties in GCM output, we performed the calculations for each of the GCM experiments individually as well as the ensemble mean changes for both RCP2.6 and RCP8.5.

Our results show consistent increases in annual mean streamflow for high-latitude regions (northern North America, northern Asia), and large parts of the tropics (central Africa, southern Asia; Fig. 2a). For 25% of the global land surface area, increases in annual mean streamflow for the 2050s are consistent among all ten GCM experiments. Consistent decreases in streamflow are projected for the United States, southern and central Europe, Southeast Asia and southern parts of South America, Africa and Australia (8% of global surface area for 2050s). Water temperatures continue to increase during the twenty-first century, with distinctly larger increases for RCP8.5 (global average of 1.0 °C for 2050s) than for RCP2.6 (0.6 °C). The strongest increases in water temperature are projected for eastern North America (0.7–1.2 °C for RCP2.6–8.5 for 2050s), Europe (0.8–1.2 °C), Asia (0.6–1.2 °C) and parts of southern Africa (>2.0 °C). Moderate increases in water temperature (<1.0 °C) are projected for Southern America and central Africa, which is probably due to the dominant impact of increased evaporative cooling under warmer conditions in these tropical regions[25].

Spatial patterns of changes in hydropower usable capacities strongly correspond with the projected impacts on streamflow, showing overall increases in Canada, northern Europe, Central Africa, India and northeastern China (Fig. 3a). However, most hydropower plants (61–74% for RCP2.6–8.5) are situated in regions where considerable declines in streamflow are projected, resulting in mean reductions in hydropower usable capacity. We found reductions in the global annual hydropower capacities of 1.7–1.9% (2020s), 1.2–3.6% (2050s) and 0.4–6.1% (2080s) based on the GCM-ensemble mean for RCP2.6–8.5 (Fig. 3c). Monthly maximum reductions are 8.9–9.2% (2020s), 9.6–17% (2050s) and 8.3–24% (2080s), with 5–22% of the hydropower plants experiencing strong (>30%) reductions in monthly usable capacity for the 2050s.

Thermoelectric power usable capacities are projected to decrease for 81–86% (RCP2.6–8.5) of the power plants in this study (Fig. 3b). Although a larger part of the world's land surface will experience increases in streamflow (Fig. 2a), most thermoelectric power plants are situated in areas with expected declines in mean annual streamflow combined with strong water temperature increases, which both amplify restrictions on cooling water use. For thermoelectric power plants in India and Russia climate change may reduce impacts of water constraints because of increasing streamflow combined with only moderate increases in water temperature. Worldwide annual mean trends (Fig. 3c) however show considerable reductions in thermoelectric power usable capacity of 5.8–5.3% (2020s), 7.0–12% (2050s) and 6.7–19% (2080s) for RCP2.6–RCP8.5. For 66–70% of the thermoelectric power plants in our study, monthly maximum reductions in usable capacity are expected to increase strongly (>30%) for the 2050s.

In a next step, we developed and tested a set of adaptation options to mitigate the vulnerability of the electricity sector to future water constraints under changing climate. We focused on six options: (1,2) increases in efficiencies of hydropower plants and thermoelectric power plants; (3) replacement of fuel sources of thermoelectric power plants (coal- and oil-fired plants replaced by gas-fired plants); (4) replacement of once-through cooling systems by recirculation (wet tower) cooling systems; (5) switch to seawater cooling for thermoelectric power plants close to the coast (<100 km); and (6) decoupling from freshwater resources by switch to seawater and dry (air) cooling for 10% of the thermoelectric power plants that are most vulnerable to water constraints under climate change (Supplementary Section 5).

Technological change in the energy sector is generally characterized by inertia due to the long-lived energy infrastructure. Historically, however, rapid changes have occurred in the case of targeted policies, such as the introduction of nuclear power in France (1970s–1980s; ref. 26) or environmental regulations to control sulphur emissions[27]. We assume in this study that adaptation occurs as sudden shifts during the start of the 2020s period. Although these shifts are not meant to be realistic representations of the diffusion speed, this assumption allows us to directly assess the impacts of these adaptation options on the vulnerability to water constraints for the selected future time slices compared with the control period.

Analysis of the various adaptation options shows that increasing total efficiencies of hydropower plants up to 10% (that is, efficiency of for example, 0.82 will become 0.90) is able to completely offset the mean annual impacts of increased water constraints under changing climate for most regions (North America, Europe, Africa and Asia; Fig. 4a). However, on the monthly level still reductions are found under a 10% efficiency increase (worldwide mean maximum reductions of 1.0–6.2% for RCP2.6–8.5 (2050s)). For South America and Australia, the GCM-ensemble mean changes show still small reductions in mean annual hydropower usable capacity. However, the range indicating the uncertainties in hydropower capacity among the different GCM experiments is largest in both regions and shows both negative and positive signals of change (Fig. 4a and Supplementary Table 4).

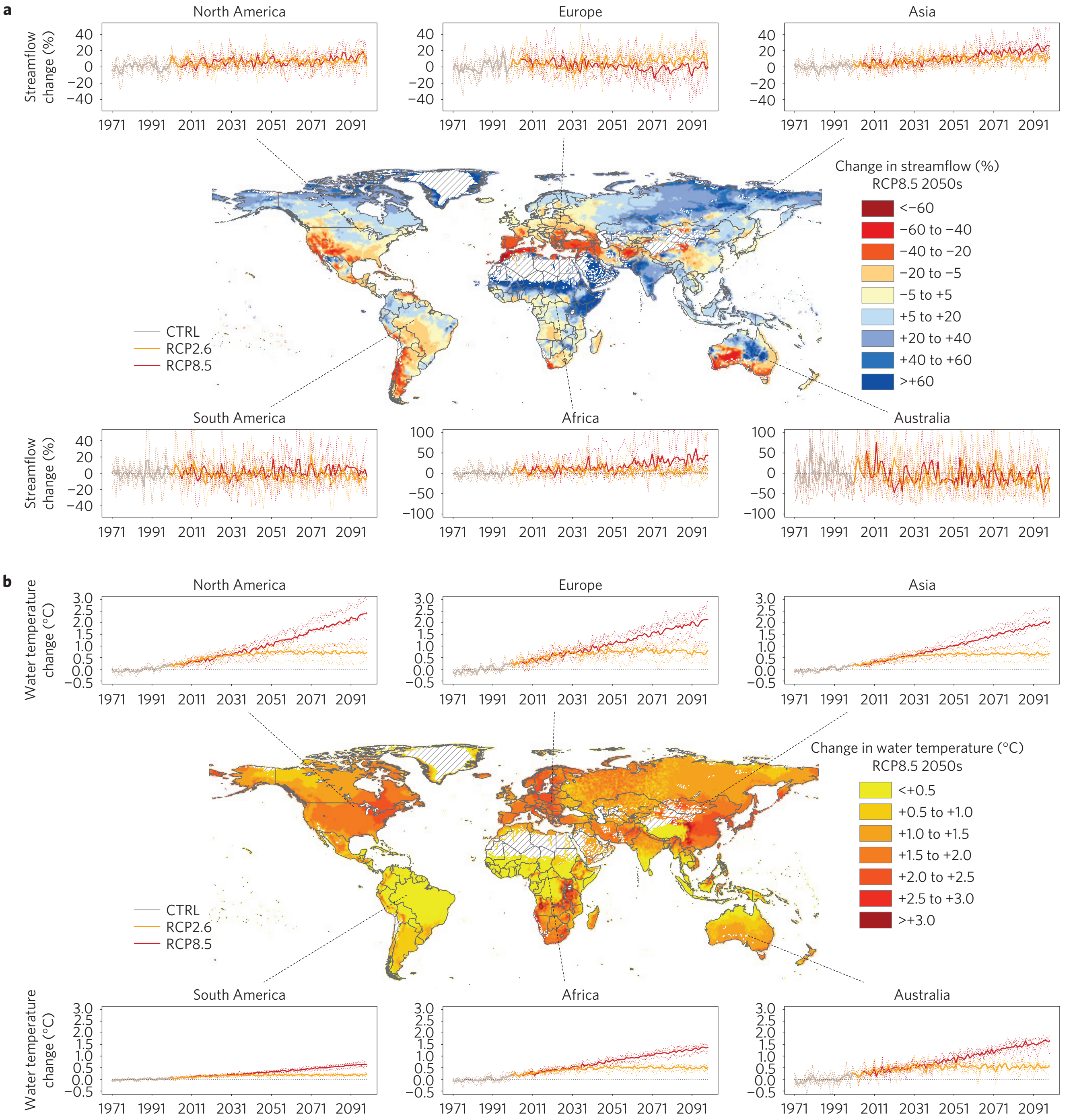

Figure 2 | Impacts of climate change on annual mean streamflow and water temperature. a,**b**, Maps of changes in streamflow (**a**) and water temperature (**b**) for RCP8.5 for 2040–2069 (2050s) relative to the control period 1971–2000. Trends in changes for 1971–2099 are presented based on the GCM-ensemble mean results (thick lines) and for the five individual GCMs separately (thin dotted lines) for both RCP2.6 (orange) and RCP8.5 (red). Trends per continent were assessed by calculating mean values in streamflow and water temperature over all continent grid cells. Future changes were then calculated relative to the control period 1971–2000.

For thermoelectric power, increased power plant efficiencies also positively contribute in reducing water demands and decreasing the vulnerability to water constraints under climate change (Fig. 4b). However, a strong increase in power plant efficiencies up to 20% (that is, efficiency of, for example, 0.45 will become 0.54) is for most regions still insufficient to mitigate overall reductions in cooling water use potential under changing climate. Changes in sources of fuel are for most regions more effective in reducing plant vulnerabilities to water constraints. On average globally, fuel switching to higher efficiency gas-fired plants with lower cooling water demands can be sufficient to mitigate plant vulnerability to water constraints for the 2020s (+2.5% to +2.8% for RCP2.6–8.5) and for the 2050s under a low concentration (+1.2% for RCP2.6). However, this adaptation option will be insufficient for North America, Europa and Asia under high concentrations for the 2050s (−4.0% for RCP8.5 worldwide). The strongest positive impacts were found for Africa and Australia, where the relative number of coal-fired plants that can be substituted by gas-fired plants is high (Supplementary Fig. 3).

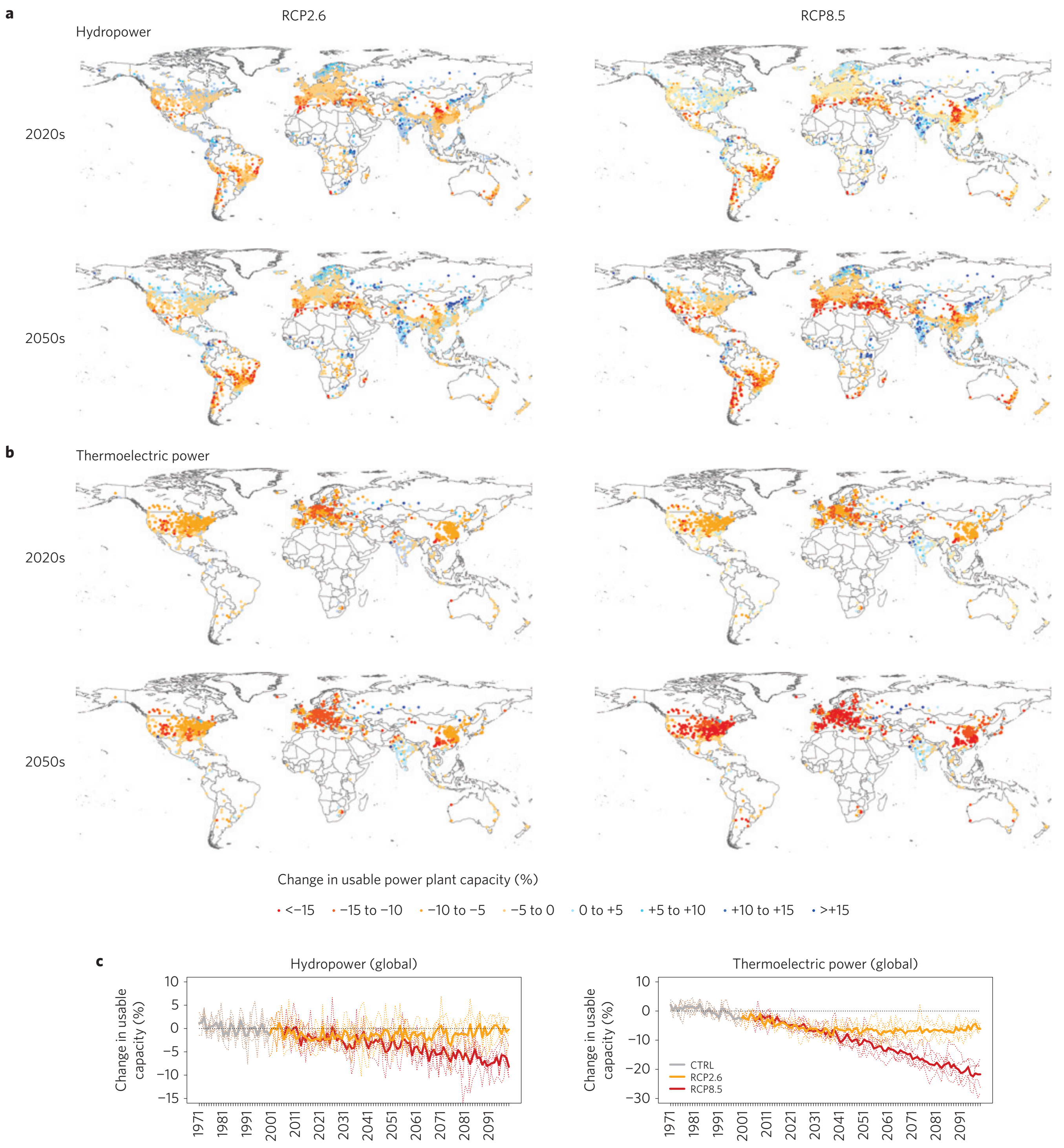

Figure 3 | Impacts of climate and water resources change on annual mean usable capacity of current hydropower and thermoelectric power plants. **a**,**b**, Relative changes in annual mean usable capacity of hydropower plants (**a**) and thermoelectric power plants (**b**) for RCP2.6 and RCP8.5 for 2010–2039 (2020s) and 2040–2069 (2050s) relative to the control period 1971–2000. **c**, Global trends of changes in annual mean hydropower and thermoelectric power usable capacity for 1971–2099 based on the GCM-ensemble mean results (thick lines) and for the five individual GCMs separately (thin dotted lines) for both RCP2.6 (orange) and RCP8.5 (red).

A switch to recirculation (wet tower) cooling decreases water withdrawals and reduces plant vulnerabilities to water constraints. This can result in smaller reductions or even slight increases in usable capacities (+3.7 to +4.0% (2020s) and +2.4 to −2.9% (2050s)), which indicates that adaptation can more than offset the impacts of climate change. A switch from freshwater cooling to seawater cooling for plants along the coast also reduces vulnerabilities to freshwater constraints. However, a decoupling of cooling water systems from freshwater resources for the 10% most severely impacted plants is a more effective adaptation option. When we assume a decoupling from the freshwater system by a switch to seawater cooling and dry (air) cooling (including also efficiency losses), we obtain a global average increase in usable thermoelectric power capacity of +8.2 and +8.6% (2020s) and +7.4 and +3.7% (2050s)

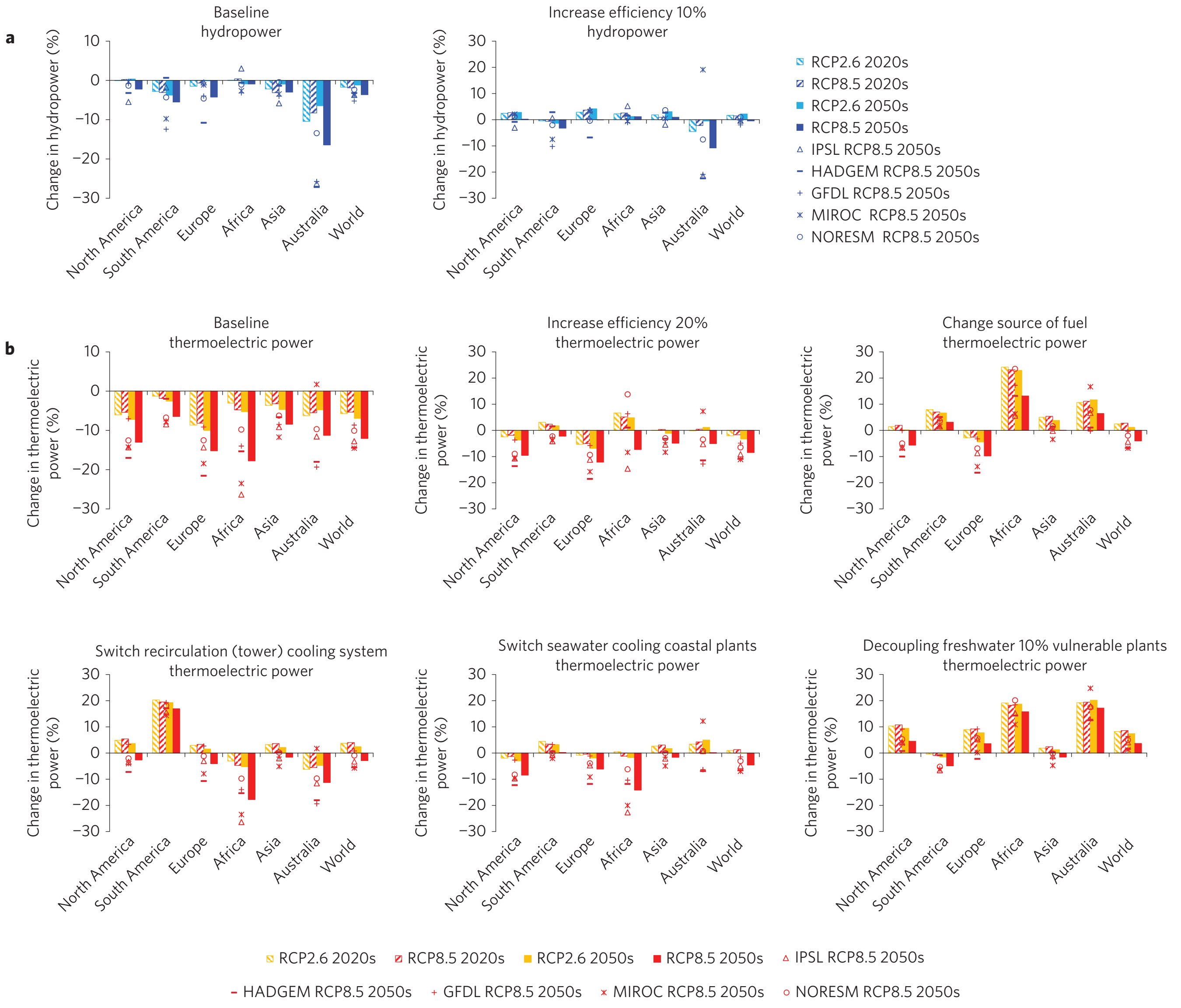

Figure 4 | Impacts of adaptation options on power-generation vulnerability to water constraints under climate change. a,**b**, Relative changes for the baseline settings and for various adaptation options of hydropower (**a**) and thermoelectric power (**b**). The GCM-ensemble mean changes are presented by the bars. In addition, changes for the five individual GCM experiments for RCP8.5 (2050s) are presented to show the range between the five different GCM experiments (see Supplementary Section 5 and Supplementary Tables 4 and 5 for more detailed results).

for RCP2.6 and RCP8.5, respectively (Supplementary Section 5 and Supplementary Table 5).

We find that climate change will reduce the existing power plant capacities of both hydropower and thermoelectric power in most regions worldwide. Socio-economic development (for example, expansion of installed capacities) could potentially further amplify freshwater constraints for these power plant capacities. A comprehensive understanding of future water constraints requires incorporating the physical impacts from our paper into economic models of the energy system. Such an integrated approach would allow more realistic projections of future hydropower and thermoelectric power generation, informed by economic, technical and physical constraints.

Our results show higher reductions in usable capacity for thermoelectric power plants (annual mean reductions of 7.0–12% for 2050s) than hydropower plants (1.2–3.6%), because of constraints in both the availability and temperatures of water resources for cooling of thermoelectric power. Considering the increase in impacts of water constraints on power generation and the long design lifetime of power plant infrastructure (∼30–60 years for thermoelectric power and 80 years for hydropower)[28], adaptation options should be included in today's planning to fulfil the growing electricity demands in the next decades[29]. We show that increased hydropower plant efficiencies up to 10% are effective to mitigate mean annual impacts of increased water constraints under climate change at most hydropower plant sites. For thermoelectric power, decoupling of cooling systems from freshwater resources by using both seawater cooling and dry (air) cooling systems is an effective alternative. However, dry cooling technologies have cost and performance (efficiency) disadvantages, and this can result in increases in the levelized cost of producing electricity of 3–8% (ref. 30). Combinations of various adaptation options (that is, increased efficiencies, changes in cooling system types and fuel switching) might therefore be a more effective strategy in reducing the impacts of water constraints on global electricity supply. A stronger focus of the electricity sector on adaptation, in addition to mitigation, is thus highly recommended to sustain water–energy security in the next decades.

Methods

Methods and any associated references are available in the online version of the paper.

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Author contributions

M.T.H.v.V. designed the study and performed all analyses with input from K.R. and D.W. S.L. assisted in preparing the global data set of power plants. M.T.H.v.V. drafted the manuscript. All authors discussed the results and contributed to the manuscript.

Additional information

Supplementary information is available in the online version of the paper. Reprints and permissions information is available online at www.nature.com/reprints. Correspondence and requests for materials should be addressed to M.T.H.v.V.

Competing financial interests

The authors declare no competing financial interests.

Methods

We used a global hydrological–electricity modelling framework to simulate streamflow, water temperature, hydropower and thermoelectric power usable capacity. The hydrological part of the modelling framework consists of the variable infiltration capacity model[18] and the physically based stream temperature river basin model[19], which run on a daily time step and at 0.5° × 0.5° spatial resolution globally. These models were linked to hydropower and thermoelectric power models (Supplementary Section 1, equations (1)–(3)) to simulate the physical impacts of water constraints on usable power plant capacity under current and future climate. Our spatially explicit global approach is developed with the aim of analysing impacts over large groups of power plants per region and to identify critical regions (hotspots) worldwide. It does however not reveal the vulnerability of any particular power plant for which specific local conditions should be included[17].

The modelling framework was applied to 24,515 hydropower plants and 1,427 thermoelectric power plants. Information on power plant characteristics was obtained from the World Electric Power Plant Database[31] and additional analyses were performed to derive the latitude–longitude of each power plant (see Supplementary Section 2). We focused on thermoelectric power plants using river water for cooling. Other criteria that we used to select hydropower and thermoelectric power plants are discussed along with the baseline power plant settings in Supplementary Section 2.

The global hydrological–electricity modelling framework was evaluated using observed daily records of streamflow and water temperature for 1,557 streamflow stations and 438 water temperature stations worldwide for 1981–2010. In addition, annual records of reported hydropower and thermoelectric power generation (1981–2010) at country level from the U.S. Energy Information Administration[1] were used to assess the quality of simulated hydropower and thermoelectric power usable capacity. This showed an overall realistic representation of the observed conditions (Supplementary Section 3 and Supplementary Figs 5–8). In addition, sensitivity analyses showed moderate impacts of uncertainties in the statistically derived parameter estimates of the hydropower and thermoelectric power models on the main outcomes of this study (Supplementary Section 3, Supplementary Tables 1–3 and Supplementary Fig. 9).

The modelling framework was forced with bias-corrected[22] general circulation models (GCMs) output from five GCMs (MIROC-ESM-CHEM, IPSL-CM5A-LR, HadGEM2-ES, NorESM1-M and GFDL-ESM2M) and for the representative concentration pathways (RCPs) 2.6 (ref. 23) and 8.5 (ref. 24) for 1971–2099. Both RCPs were selected to capture the largest range of uncertainties in radiative forcing under future greenhouse gas emissions (Supplementary Section 4).

To assess effective strategies for reducing the vulnerability of the electricity sector to climate change and increasing water constraints, we tested a set of six different adaptation options: 1. Increases in total efficiencies of hydropower plants (up to 10%). 2. Increases in total efficiencies of thermoelectric power plants (up to 20%) 3. Replacement of fuel sources of thermoelectric power plants. Coal- and oil-fired plants are replaced by gas-fired power plants (see Supplementary Fig. 3 for baseline power plant settings). 4. Replacement of once-through cooling systems by recirculation (wet tower) cooling systems for thermoelectric power plants (see Supplementary Fig. 4 for baseline power plant settings). 5. Switch to seawater cooling for all thermoelectric power plants within a zone less than 100 km from the coastal line (see Supplementary Fig. 11). 6. Decoupling from freshwater resources by switching to seawater cooling and dry (air) cooling systems for 10% of the thermoelectric power plants that are most vulnerable to increasing water constraints under climate change (see Supplementary Fig. 12). We assumed that the most vulnerable plants within a 100 km range from the coastal line are likely to switch to seawater cooling and inland-located plants were assumed to switch to dry (air) cooling. For the switch to dry cooling, we included an efficiency loss of 6%, which is the median value based on the efficiency loss range of 2–10% reported in ref. 32 (Supplementary Section 5).

All six adaptation options were assumed to occur as sudden shifts during the start of the 2020s period to directly assess the impacts of these adaptation options on the vulnerability to water constraints for future time slices compared with the control period.

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