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Climate change impacts and greenhouse gas mitigation effects on U.S. hydropower generation

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HIGHLIGHTS

- Analyze contiguous U.S. hydropower generation under various emissions scenarios.
- Employ systems model that allocates water to competing uses in 2119 river basins.
- Average U.S. generation increases under climate change, but falls under low flows.
- Mitigation benefits are $2-$4 billion/year due to high values of carbon-free energy.

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ABSTRACT

Climate change will have potentially significant effects on hydropower generation due to changes in the magnitude and seasonality of river runoff and increases in reservoir evaporation. These physical impacts will in turn have economic consequences through both producer revenues and consumer expenditures. We analyze the physical and economic effects of changes in hydropower generation for the contiguous U.S. in futures with and without global-scale greenhouse gas (GHG) mitigation, and across patterns from 18 General Circulation Models. Using a monthly water resources systems model of 2119 river basins that routes simulated river runoff through reservoirs, and allocates water to potentially conflicting and climate dependent demands, we provide a first-order estimate of the impacts of various projected emissions outcomes on hydropower generation, and monetize these impacts using outputs from an electric sector planning model for over 500 of the largest U.S. hydropower facilities. We find that, due to generally increasing river runoff under higher emissions scenarios in the Pacific Northwest, climate change tends to increase overall hydropower generation in the contiguous U.S. During low flow months, generation tends to fall with increasing emissions, potentially threatening the estimated low flow, firm energy from hydropower. Although global GHG mitigation slows the growth in hydropower generation, the higher value placed on carbon-free hydropower leads to annual economic benefits ranging from $1.8 billion to $4.3 billion. The present value of these benefits to the U.S. from global greenhouse gas mitigation, discounted at 3%, is $34 to $45 billion over the 2015–2050 period.

1. Introduction

Understanding the benefits of reducing greenhouse gas emissions in the United States is important to make informed decisions about climate change mitigation options. The U.S. Environmental Protection Agency (EPA) initiated the Climate Change Impacts and Risk Analysis (CIRA) project to achieve this objective, bringing together multiple, national-scale models to quantify and monetize the multi-sector risks of inaction on climate change and the benefits of global greenhouse gas (GHG) mitigation, using a consistent set of climate models and emissions scenarios [1]. With approximately 88% of electricity generated by technologies that require water for cooling [2], and an additional 7% generated by hydropower facilities [3], the U.S. electricity sector stands to be heavily affected by projected changes in temperature and precipitation,

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and thus by the climate change limiting effects of GHG mitigation. Although hydropower generation makes up a relatively small share of the national total, the share is much larger in certain regions such as the Pacific Northwest where over half of total generation comes from hydropower, and represents the majority of the renewable portfolio of many states. Under climate change, hydropower generation is likely to be significantly affected due to increasingly variable precipitation and river runoff, and rising reservoir evaporation [4].

In this research, we analyze the physical and economic effects of climate change on hydropower generation in the contiguous U.S. (CONUS). We use a monthly water resources systems model of 2119 river basins with over 500 of the largest hydropower facilities to evaluate the effects of global-scale greenhouse gas (GHG) mitigation compared to a future with no emission reductions. This research is the first to incorporate an extensive network of reservoirs and the effect of potentially competing and climate dependent water demands across CONUS in an analysis of climate change effects on hydropower generation. While it was infeasible to accurately capture the impact of monthly management and operation in each of these reservoirs and hydropower facilities, these results provide a first-order estimate of the physical and economic benefits of global action to limit GHG emissions in the realm of changes in U.S. hydropower generation.

Prior studies have examined the impacts of climate change on hydropower generation at the U.S. national-scale, but to our knowledge, none have done so using a detailed water systems model with hydropower modeled at the facility-level. Henderson et al. [5] use a CONUS-scale simulation-optimization model to generate economic impacts to hydropower and other water-dependent sectors for 99 sub-catchments of the U.S. Those authors find that GHG mitigation reduces CONUS hydropower generation, but this effect is primarily due to increases in runoff in a business as usual climate scenario, which the model interprets to increase hydropower production, though it is not clear that all or even most hydropower facilities are equipped with the turbine and reservoir capacity to effectively exploit additional runoff. They model hydropower for a single year under each scenario using simplified runoff scaling factors in each of the 99 basins, whereas the current work explicitly models facility-level hydropower generation over a 30-year period to capture variability under each scenario based on potentiometric head, maximum turbine capacity, and other facility characteristics.

In another CONUS-focused study, Lettenmaier et al. [6] estimated the impact of climate change on six U.S. reservoir systems, including the potential impact on hydropower generation. Of the four reservoir systems for which hydropower production is a major use, all showed an expected decrease in reliability of power generation under the majority of climate scenarios considered. In a qualitative study, Schaeffer et al. [7] identified the main ways in which climate change will affect the energy sector, and point out existing knowledge gaps and recommended future directions for research. One of their primary recommendations is that studies consider a broader range of climate scenarios when conducting energy vulnerability analyses – the current study considers a total of 54 climate model-emissions scenario combinations.

Sale et al. [8] use river runoff simulations to analyze the impact of a business-as-usual climate scenario on hydropower production at Federal hydropower operations in the U.S., and find a median decrease in annual generation of approximately 2000 gigawatt-hours (GW h), or about 2% of total U.S. generation. However, this research did not incorporate reservoir management or supply–demand balancing, and focused on only a single GHG emissions and climate scenario. Madani and Lund [9] construct an Energy-Based Hydropower Optimization Model (EBHOM) to simulate hydrological changes and the resulting impact on hydropower generation. While this is a similar goal to our current research, the study focuses only on high-altitude hydropower plants in California, and the model is designed for that region. Hurd et al. [10] use a national model of hydropower production for 18 aggregated river basins of CONUS, and find that under a range of climate change scenarios, the value of hydropower production changes between −51% and +5%. These large CONUS-wide reductions in production differ from findings in the current work, which suggest increases in generation under climate change due to generally increasing runoff in the Pacific Northwest. The differences may be attributable to the climate scenarios employed, the much more aggregated analysis in the earlier work, or other factors.

Multiple studies have had an international or global focus. Hamududu and Killingtveit [11] use simulations of regional runoff patterns with varying climate models to predict changes in hydropower generation potential. This study found that, while total generation across the globe was largely unchanged, regional increases or decreases in hydropower production were quite large. Another, similar study by Van Vliet et al. [12] focuses on global vulnerability of hydropower production to climate change. The analysis used outputs from five GCMs to generate predictions under a variety of climate conditions. This study found that, while overall increases in streamflow are expected in many regions, most existing hydropower plants are located in areas where streamflow is expected to decline, resulting in an overall loss of global hydropower capacity. Raje and Mujumdar [13] study overall performance of reservoirs in India, for multiple purposes including irrigation, flood control, and hydropower production, under three GCMs and for three climate scenarios during the remainder of the century. The authors propose optimal reservoir operation policies for each scenario, and also find that, due to increased irrigation needs, hydropower generation would fall below current levels under any scenario. Importantly, unlike the current work, these other studies do not consider climate-change induced changes in non-hydropower demands, or the effect of river infrastructure on hydropower production.

As described below, changes in irrigation water demand have been integrated into the current model, but increases in water demand related to the need to cool thermal generation plants are not yet considered. Adding estimates of this facet of climate sensitive water demand would be an important potential improvement on our work, as demonstrated by previous work (e.g., [14,15]). Our model is capable of incorporating the climate-induced demand for thermal cooling water in future research.

2. Methodological approach

We employ a set of linked models to assess the effects of climate change on hydropower generation in futures with and without global-scale GHG mitigation (Fig. 1). Projections of temperature and precipitation from General Circulation Models (GCMs) are input into: (a) a water demand model, which projects the water requirements of the municipal and industrial (M&I) and agriculture sectors in each of the 2119 CONUS basins; and (b) a rainfall-runoff model that is used to simulate monthly runoff in each basin. A water resources systems model then uses these availability and demand projections to produces a time series of reservoir storage, release, and allocation to the various demands in the system. In addition to irrigation and M&I demands, environmental flows, transboundary flows, and hydropower are also included in all applicable basins (see [16] for more details). Lastly, hydropower generation is valued using annual electricity prices produced from an electric sector planning model of the U.S. to estimate economic implications with and without GHG mitigation. Each of these main modeling components are described in more detail below.

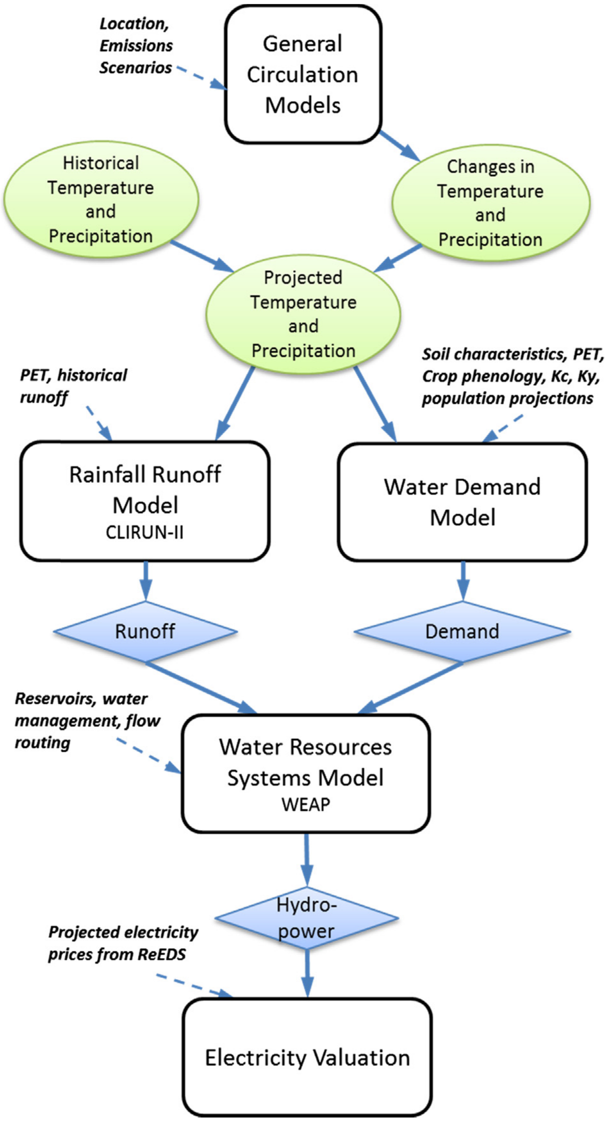

Fig. 1. Analytical framework.

2.1. Emission scenarios and climate projections

Climate projections under a range of emissions scenarios allow us to estimate the benefits of GHG mitigation and how those benefits evolve over time. We first develop a control scenario that represents present day climate climatic conditions but includes population change and thus changes in M&I water demand. The control scenario is then altered to incorporate climate change projections, and the resulting hydropower output across each emission scenario and climate projection is measured. Descriptions of the global GHG mitigation scenarios are provided by Paltsev et al. [17] and Waldhoff et al. [1], along with a comparison to the representative concentration pathways (RCPs) from the Intergovernmental Panel on Climate Change (IPCC). Because this analysis is part of the CIRA project mentioned above, it employs a consistent set of socioeconomic and climate scenarios to facilitate comparisons across sectors. These include three emission scenarios, each with a climate sensitivity of 3 degrees C: a reference (REF) or 'business as usual', and two scenarios representing policies that limit global GHG emissions such that by 2100, total radiative forcing levels are stabilized at 4.5 W/m^2 (Pol4.5) or 3.7 W/m^2 (Pol3.7). Although the REF scenario has a total radiative forcing in 2100 of 10.0 W/m^2, that total declines to 8.6 W/m^2 using the IPCC simplified equations, and is therefore similar to RCP 8.5. The level of global GHG mitigation achieved under the Pol3.7 scenario is consistent with the amount required to meet the 2 °C target relevant to recent international climate negotiations. Monier et al. [18,19] present the base framework used to project future climate, the Community Atmospheric Model linked with the MIT Integrated Global Systems Model (IGSM-CAM), and also provide a summary of the regional projections of climate change used in this study.

Since the IGSM-CAM only considers a single GCM, the IGSM pattern scaling approach was used to develop a balanced set of regional patterns of climatic change for CONUS (see [20,19] for details). This approach preserves all the CIRA economic and emissions drivers of the scenarios, but replaces the CAM climate projections with projections based on alternative spatial patterns. Seventeen GCMs from the IPCC AR4 climate models were selected for the pattern-scaled results, each with different patterns of change over CONUS [20]. Monier et al. [19] discuss how the IGSM-CAM simulations compare to the pattern-scaled projections, as well as the limitations of both methods. We employ both the IGSM-CAM climate projection and the 17 pattern scaled GCM projections in this study. The climate projections for each of the three emission scenarios are split into two 30-year eras centered around 2025 and 2050. Each era is represented by monthly climate variability from 1979 to 2008 (sourced from Sheffield et al. [21]) with changes in climate applied.[1]

2.2. Runoff, water demand, and water systems models

The climate projections for each emission scenario were used to develop monthly runoff estimates. Runoff modeling converts the climate shifts into changes in surface water availability important for the water resource systems model. Surface water runoff was modeled with the rainfall-runoff model CLIRUN-II (see [22,23]), the latest available application in a family of hydrologic models developed specifically for the analysis of the impact of climate change on runoff, first proposed by Kaczmarek [24].[2] Fig. 2 shows the ensemble mean percentage change in projected runoff to 2050 across the 17 pattern scaled runs, under each of the three emissions scenarios. There is a clear intensification of runoff changes between the policy and REF scenarios, and the bulk of northern and western CONUS shows increasing runoff conditions.

Water demands are the other side of the water balance, and are developed using 2005 data from the U.S. Geological Survey on annual water withdrawals and consumptive use in a range of sectors including irrigation, M&I use, mining, thermal cooling, and several other sectors [29]. These data are available at the 3109 counties of CONUS and spatially averaged to the 8-digit HUC resolution using the same approach taken by the U.S. Forest Service in their development of the Water Supply Stress Index (WaSSI; [30]).

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[1] For precipitation, we use a simple ratio method where the change in precipitation is expressed as the future monthly mean precipitation divided by the historical monthly mean precipitation. For temperature, we use a simple "delta" method, where changes in temperature are expressed as differences between the mean monthly modeled historical temperature and projected future temperature.

[2] As described in further detail by Boehlert et al. [16], CLIRUN-II simulates runoff at a monthly time step, at a gauged location at the mouth of the catchment. Climate inputs and soil characteristics are averaged over each of the 8-digit HUCs. Following the SIXPAR hydrologic model framework [25,26], CLIRUN-II employs a two-layer approach. Calibration coefficients that characterize each of the 2119 catchments are defined using a pattern search algorithm that minimizes the sum of square errors between observed and simulated runoff. As the CONUS 8-digit HUCs currently have no naturalized runoff dataset, model calibration was based on naturalized runoff data for 99 basins of CONUS from USWRC [27] allocated to the underlying 8-digit HUCs based on mean annual 1971–1980 precipitation from the PRISM dataset [28].

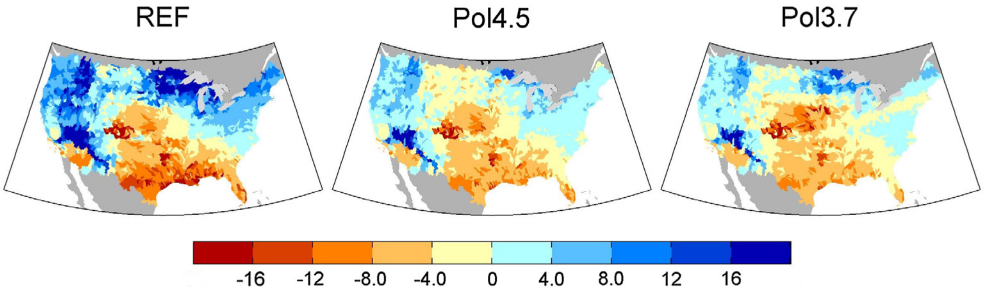

Fig. 2. Ensemble mean percentage change in projected runoff across the 17 pattern scaled GCMs for each 8-digit HUC under each emissions scenario for 2050, relative to the historical modeled run.

We then input the simulated runoff and projected water demands into a well-established river basin systems modeling software (see [31]) to simulate reservoir management and routing. The 2119-basin CONUS model optimizes water allocation based on a prescribed set of priorities, and simulates the sequence of existing reservoir activity and demands that each compete for water and are dependent on upstream/downstream routing. Boehlert et al. [16] provide additional details on the CLIRUN-II model calibration procedures and dataset; modeling of the base and projected M&I demands and irrigation withdrawals; and the water systems model.

2.3. Hydropower system

To parameterize the hydropower component of the water resources systems model in each 8-digit HUC, we rely on physical characteristics of reservoirs from the U.S. Army Corps of Engineers [32], and facility-level installed capacities from the EW3 database from the Union of Concerned Scientists [2]. In smaller facilities that were not identifiable in the Corps database, we aggregated 8-digit HUC storage from the Corps and total installed capacity from UCS, and then assumed a relationship between volume and elevation from which we back-calculate maximum flow through turbines. This operation provided the inputs needed for the WEAP model. To ensure that our installed capacities matched data inputs from a well-recognized U.S. electricity planning model, we calibrated facility capacities using the data available for the 134 balancing areas of the National Renewable Energy Laboratory (NREL) Regional Energy Deployment System (ReEDS) model [33]. As shown in Fig. 3, the large majority of hydropower capacity in the U.S. is within the Pacific Northwest, California, and the Southeast.

Hydropower generation also depends on operating strategy and river flows, both of which are uncertain due to the absence of a U.S.-wide source for these data (see discussion above). Owing to these uncertainties, our model of CONUS hydropower produces an average of approximately 90% of the 262 terawatt-hours (TW h) generated annually across CONUS (excluding the Great Lakes 2-digit HUC) based on NREL data over the 2004–2013 period.[3] Although the modeled generation is biased downward, in part because we focus on the largest roughly 500 facilities, the broader purpose of this work is ultimately to evaluate the relative changes under climate change, and the effect of global GHG mitigation. Fig. 4 provides the relationship between the modeled versus observed average annual hydropower generation over the 1980–2009 baseline for the 4-digit HUCs, both in $\log_{10}$ space to reduce the influence of large values. To develop the 4-digit HUC data, we spatially aggregated a version of the UCS facility-level data that was calibrated to ReEDS generation in each of the 134 balancing areas. Fig. 4 shows a strong fit between mean annual modeled and observed generation albeit with a few outliers showing low modeled generation. Many of these low outliers are in California, which has a particularly complex water management system and has several large pumped storage facilities in the Sierras.

2.4. Valuation of hydropower

The economic value of the change in hydropower generation estimated using projections of power prices from the ReEDS model under a consistent set of climatic and policy assumptions (see [34]). Scenarios modeling reductions in GHG emissions assume that supply-side costs in the electric sector associated with shifting the generation mix are incorporated into the price of electricity. We consider an illustrative electricity price scenario that includes the marginal costs of CO_2 emission reductions (i.e., a carbon price). Electricity prices inclusive of CO_2 reduction costs show higher prices under the mitigation scenarios (e.g., prices in 2050 range from $115/MW h in the REF scenario, $120/MW h in Pol4.5, and $127/MW h in Pol3.7 in 2005$). Note that these results do not consider second order feedbacks between hydropower production, prices, and production from other sources; to fully capture these economic effects to changes in hydropower generation, we would iterate our model with an electric sector planning model such as ReEDS.

3. Results

Under the IGSM-CAM projections and average of the 17 pattern scaled GCM projections, hydropower generation across CONUS increases under each of the future emissions scenarios, for both the 2025 and 2050 eras, relative to the control (that is, current climate).[4] Fig. 5 provides the distribution of the changes across the 17 pattern scaled GCM projections for each of the emissions and climate sensitivity scenarios. Generally, average CONUS hydropower generation increases with time and emissions. However, there is wide variation across the GCM projections. By 2050 and under the REF scenario, the 5th to 95th percentile of changes in generation over the control range from −14% to +28%, with an average of +6.5%. Across CONUS, global GHG mitigation reduces both the maximum increases and decreases in generation resulting from climate change

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[3] Note that these figures and this analysis exclude generation in the Great Lakes 2-digit HUC, which contains the Robert Moses Niagara and Ludington Power Plants. Modeling hydropower production in this HUC, which depends heavily on pumped storage and highly complex management, is beyond the scope of this CONUS-scale study.

[4] Note that differences between the historical baseline and the 2050 control scenario are minimal, as the control scenario includes no changes in climate or agricultural water use patterns, only changes in M&I use driven by population growth and migration and reductions in per capita use.

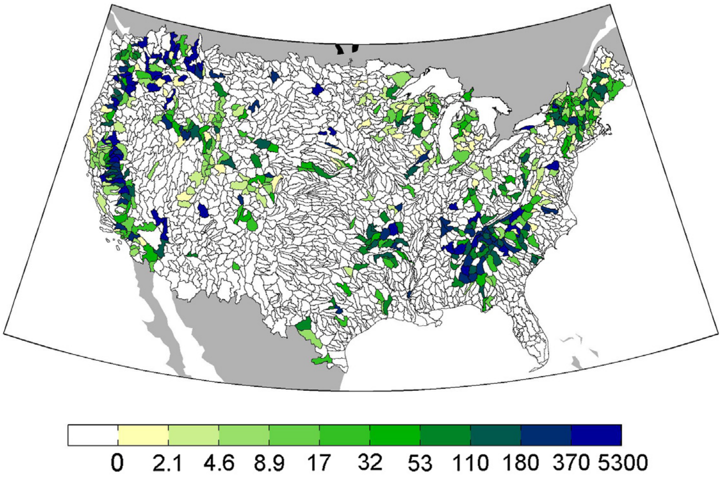

Fig. 3. Total installed hydropower capacities in each of the 8-digit CONUS HUCs (MW). Note non-linear scale. Source: NREL ReEDS model inputs [33].

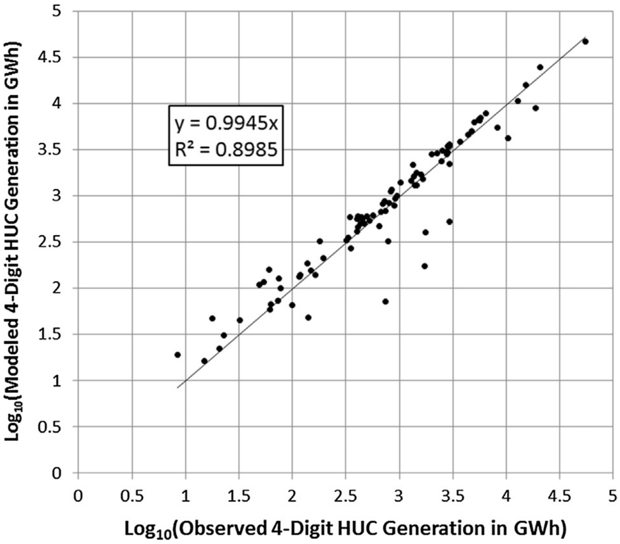

Fig. 4. Relationship between observed and modeled hydropower generation for the 4-digit HUCs of CONUS (excluding the Great Lakes 2-digit HUC) in $\log_{10}$ space. Hydropower outputs are average annual values over the 1980–2009 period.

across the GCM projections; under the Pol3.7 scenario, changes range from −13% to +13% with an average of +1%.

The spatial pattern of projected changes in generation across CONUS reveals why we see consistent increases in average generation across the climate change scenarios. Average changes in hydropower generation in each of the 2-digit HUCs of CONUS are provided in Fig. 6. The Pacific Northwest region, which accounts for over 40% of U.S. annual hydropower generation, shows universal average increases across scenarios and eras. On the other hand, the regions where broad agreement in decreasing hydropower trends occur, including the southern central U.S. HUCs, tend to account for far less of U.S. generation. This pattern is reflected in projected changes in mean annual runoff (Fig. 2), which increase in the Pacific Northwest and decrease across large regions of the central U.S.

Table 1 presents these average annual changes for each of the 8-digit HUCs in absolute terms (GW h/yr). By 2050, generation across CONUS is projected to increase by approximately 6.5 TW h/yr under the REF scenario, and 1.3 TW h/yr under the POL3.7 scenario. In both 2025 and 2050, these increases in generation under the REF emissions scenario are primarily driven by much higher production in the Pacific Northwest, which by 2050 increase 8.0 TW h/yr. These are partly counterbalanced by changes in the southern central HUCs (South Atlantic Gulf, Tennessee, Lower Mississippi, Arkansas-White-Red, Texas Gulf, and Rio Grande), where generation by 2050 declines by 1.2 TW h/yr in REF, and 0.8 TW h/yr in POL3.7.

In addition to average annual generation, seasonal and year-to-year variability in electricity production are important for ensuring firm energy. Table 2 shows the average seasonal change in generation to 2050 across 2-digit HUCs and emissions scenarios. The large increases in generation are the result of increases in the win-

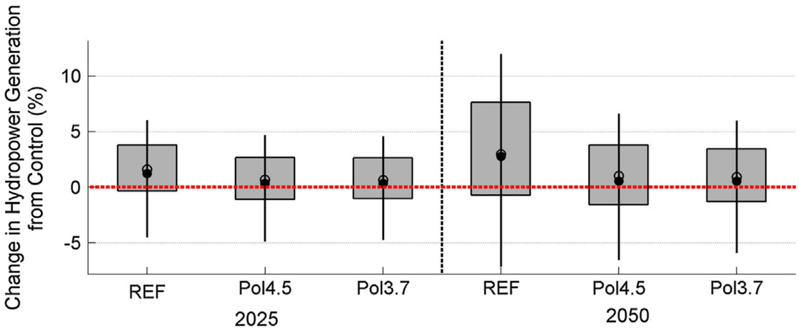

Fig. 5. Change in average annual hydropower generation (%) across the 17 pattern scaled GCMs for 2025 and 2050, and under each of the climate emissions scenarios, relative to current climate. In each boxplot, the box represents the 25th to 75th percentile, and the whiskers span the 5th to 95th percentile. The black dot is the mean across the 17 GCMs and the open circle is the median.

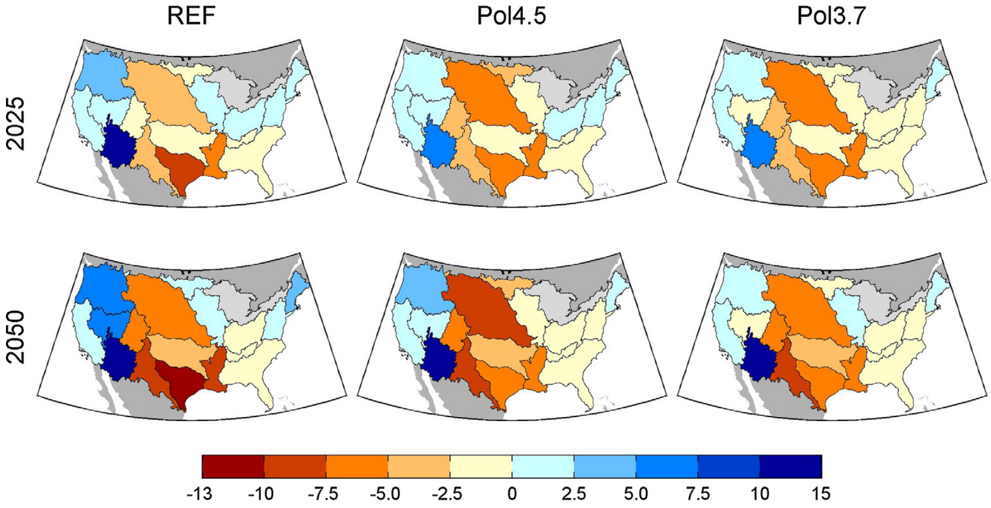

Fig. 6. Average percentage change in hydropower generation across the 17 pattern scaled GCMs for each 2-digit HUC under each emissions scenario for 2025 and 2050, relative to the current climate control.

Table 1
Average annual change in 2025 and 2050 hydropower generation (GW h) from control, at the 2-digit HUC level, under the average across pattern scaled GCM projections. Note: excludes the Great Lakes 2-Digit HUC.

2-Digit HUC	2025			2050		
	REF	POL4.5	POL3.7	REF	POL4.5	POL3.7
New England	132	70	16	328	111	109
Mid Atlantic	49	38	−63	17	−17	−145
South Atlantic Gulf	−107	−176	−220	−343	−236	−200
Ohio	76	13	−11	−83	−73	−95
Tennessee	−26	−89	−105	−239	−171	−143
Upper Mississippi	2	−6	−5	7	−7	2
Lower Mississippi	−69	−77	−85	−120	−94	−85
Souris-Red-Rainy	−1	−1	−1	0	−1	−1
Missouri	−385	−595	−560	−634	−892	−710
Arkansas-White-Red	−114	−159	−161	−379	−276	−242
Texas Gulf	−101	−86	−84	−142	−89	−81
Rio Grande	−10	−11	−10	−21	−18	−16
Upper Colorado	−100	−164	−177	−311	−330	−329
Lower Colorado	69	36	31	144	72	55
Great Basin	3	0	−4	17	3	−4
Pacific Northwest	3295	1905	2217	8012	3200	3134
California	189	109	74	271	100	46
TOTAL	2902	808	854	6524	1282	1294

ter and spring months (December through May), while generation typically falls in the drier summer and fall months (June through November). In the Pacific Northwest, generation in the summer months declines by 14% under the REF scenario, and only 9% under POL3.7. Generally, the largest declines occur in the summer, indicating that although mean annual generation is projected to rise, firm generation may fall.

In the U.S., firm energy is defined differently by region and is often facility-specific. As a result, accurately estimating firm energy production is well beyond the scope of this CONUS-wide study. Following Alavian et al. [35], Borges and Pinto [36] and others, to estimate impacts on reliable generation under climate change, we define an indicator of firm energy as the generation that is available 95% of months in each HUC (i.e., in our baseline and projected 360-month series, the 18th highest value). Fig. 7 presents changes in this indicator through 2025 and 2050 across the 17 pattern scaled GCMs. Owing to the lower and higher extremes under climate change, over 85% of the GCMs project declines in this indicator under all scenarios, and in 2050, those reductions are considerably more pronounced under the high emissions scenario. Fig. 8 shows these results spatially; although the reductions are greatest in the Pacific Northwest due to large projected decreases in summer runoff, the rest of CONUS also shows falling 5th percentile generation. Other studies of a similar purpose and geographic scale have applied more extreme firm energy criteria, such as World Bank [37] in a study of Zambezi hydropower generation under climate change, which defined firm energy as generation available 99% of months. In the current study, increasing the threshold to 99% would draw out the most extreme lows, which would intensify the negative effects of climate change and potential positive effects of mitigation.

As indicated above, we find that global GHG mitigation, on average, has a slight overall negative effect on U.S. hydropower generation in both eras; by 2050, mitigation reduces CONUS hydropower generation relative to the REF emissions scenario by approximately 5 TW h annually (~2%, see Fig. 9, left panel). However, by this later period, mitigation is projected to increase 5th percentile monthly generation, suggesting potential increases in firm energy (Fig. 9,

Table 2
Average seasonal change in 2050 hydropower generation from the control for each emissions scenario, at the 2-digit HUC level, under the average across pattern scaled GCM projections. Note: Excludes the Great Lakes 2-Digit HUC.

	DEC-JAN-FEB			MAR-APR-MAY			JUN-JUL-AUG			SEP-OCT-NOV		
2-Digit HUC	**REF**	**POL4.5**	**POL3.7**	**REF**	**POL4.5**	**POL3.7**	**REF**	**POL4.5**	**POL3.7**	**REF**	**POL4.5**	**POL3.7**
New England	18%	11%	10%	2%	1%	1%	-3%	-5%	-4%	0%	-1%	0%
Mid Atlantic	7%	5%	5%	-3%	-2%	-2%	-2%	-3%	-8%	-2%	-2%	-3%
South Atlantic Gulf	0%	0%	0%	-5%	-4%	-4%	-2%	-1%	0%	-2%	-1%	-1%
Ohio	1%	1%	1%	-2%	-1%	-1%	0%	-1%	-1%	-2%	-1%	-1%
Tennessee	-1%	0%	0%	-2%	-2%	-2%	-1%	-1%	0%	-2%	-1%	-1%
Upper Mississippi	1%	0%	0%	1%	0%	0%	0%	-1%	0%	0%	0%	0%
Lower Mississippi	3%	2%	2%	-18%	-14%	-13%	-18%	-14%	-13%	-6%	-4%	-4%
Souris-Red-Rainy	0%	-4%	-3%	7%	1%	0%	-4%	-5%	-1%	-3%	-4%	-2%
Missouri	-12%	-12%	-10%	14%	6%	5%	-12%	-13%	-10%	-16%	-15%	-14%
Arkansas-White-Red	1%	1%	1%	-8%	-6%	-5%	-6%	-5%	-4%	-5%	-4%	-3%
Texas Gulf	-4%	-1%	-1%	-14%	-10%	-9%	-16%	-9%	-8%	-13%	-9%	-8%
Rio Grande	-8%	-6%	-6%	-8%	-7%	-7%	-16%	-12%	-11%	-7%	-6%	-6%
Upper Colorado	-8%	-9%	-9%	7%	3%	2%	-15%	-12%	-12%	-10%	-10%	-10%
Lower Colorado	32%	14%	9%	33%	10%	7%	42%	26%	21%	3%	1%	-1%
Great Basin	14%	4%	3%	28%	16%	12%	-14%	-11%	-11%	-14%	-15%	-18%
Pacific Northwest	23%	13%	12%	14%	9%	8%	-14%	-12%	-9%	-5%	-5%	-5%
California	10%	6%	5%	7%	4%	3%	-6%	-4%	-4%	-11%	-8%	-8%
TOTAL	**13%**	**7%**	**6%**	**9%**	**5%**	**4%**	**-9%**	**-8%**	**-7%**	**-5%**	**-5%**	**-4%**

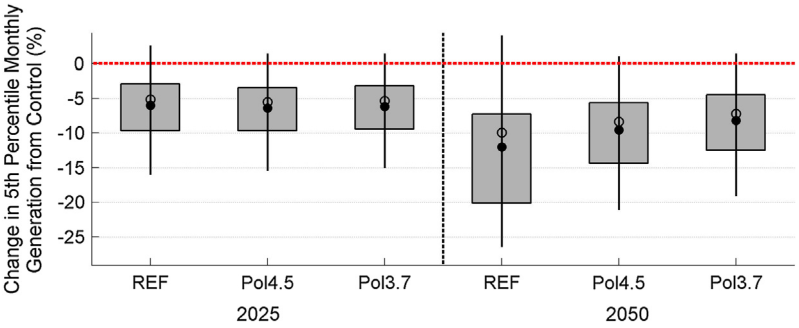

Fig. 7. Change in 5th percentile monthly hydropower generation (%) across the 17 pattern scaled GCMs for 2025 and 2050, and under each of the climate emissions scenarios. In each boxplot, the box represents the 25th to 75th percentile, and the whiskers span the 5th to 95th percentile. The black dot is the mean across the 17 GCMs and the open circle is the median.

right panel). Regionally, GHG mitigation would reduce projected average generation in the Pacific Northwest, other parts of the western U.S., and the northern U.S., while increasing projected generation in the southeast, relative to the REF Reference climate change scenario.

Next, we apply the ReEDS prices to value the changes in hydropower generation. Table 3 shows these results for the three emission scenarios, and under both the IGSM-CAM model and the mean across the 17 pattern scaling GCMs. Although hydropower generation falls by roughly 2% in the mitigation scenarios relative to the REF scenario, retail electricity price increases (e.g., 10% in the Pol3.7 scenario) more than offset the relative decline in generation and lead to positive annual net benefits. The annual benefits of reducing GHG emissions under the Pol3.7 scenario in 2025 are approximately $600 million for IGSM-CAM and $1.8 billion for the average of the 17 pattern scaled results, and in 2050, $4.3 billion for IGSM-CAM and $2.3 billion for the average of pattern scaled results.

For IGSM-CAM, the net present value of the benefits, discounted at 3%, from 2015 through 2050 for the Pol3.7 scenario is approximately $34 billion.[5] Under the pattern scaled results, the benefits range from $34 to $45 billion.

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[5] Present value calculations require an annual series of revenue estimates. To construct this series, we assumed that for each GCM and scenario, a linear trend was assumed from zero in 2015 to the average era revenue effect in 2025, and then another linear trend between the 2025 and 2050 average era revenue.

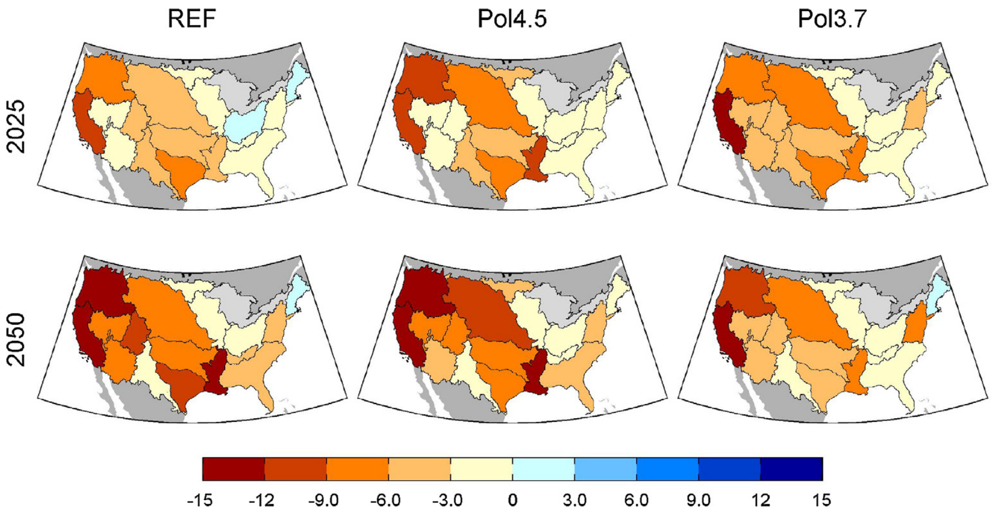

Fig. 8. Average percentage change in 5th percentile monthly hydropower generation across the 17 pattern scaled GCMs for each 2-digit HUC under each emissions scenario for 2025 and 2050, relative to the current climate control.

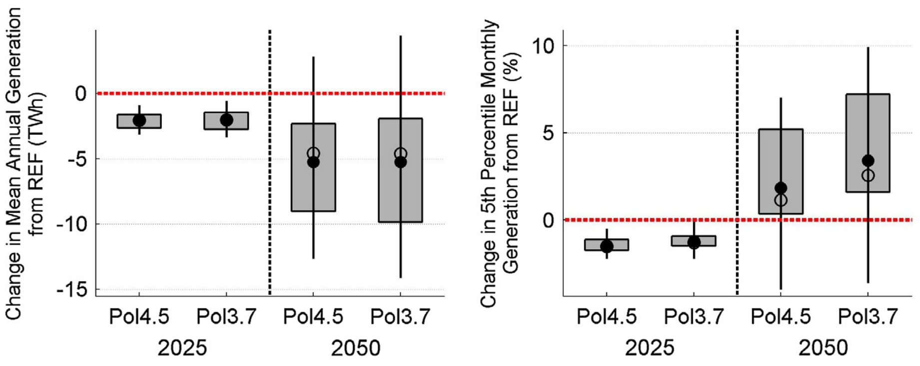

Fig. 9. Change in average annual hydropower generation (TW h; left panel) and change in 5th percentile monthly generation (%; right panel) across the 17 pattern scaled GCMs for 2025 and 2050, and under each of the climate emissions scenarios, relative to the Reference scenario. In each boxplot, the box represents the 25th to 75th percentile, and the whiskers span the 5th to 95th percentile. The black dot is the mean across the 17 GCMs and the open circle is the median.

Table 3
National average change in hydropower revenues from control in 2025 and 2050 for each scenario (millions of 2005$), under each of the ReEDS price scenarios and under the IGSM-CAM (CAM) and average pattern scaled outputs (PS mean). The change from REF for the two policy scenarios is also shown.

Year	Model	REF	Pol4.5	Pol3.7	Delta Pol4.5-REF	Delta Pol3.7-REF
2025	PS mean	$287	$1130	$2099	$843	$1812
	CAM	$3104	$3189	$3701	$85	$597
2050	PS mean	$781	$1405	$3095	$624	$2314
	CAM	$2111	$3579	$6446	$1468	$4335

4. Conclusions and further research

In this study, we have linked a network of models to assess the benefits of global-scale GHG mitigation on hydropower generation in the contiguous U.S. The analysis runs changes in climate through a water resources systems model that has over 500 hydropower facilities with installed hydropower capacities calibrated to inputs of the ReEDS electric sector planning model. Under the majority of the 18 climate models and three emissions scenarios considered, total CONUS hydropower generation rises under climate change. This is predominantly driven by the large projected increases in mean annual runoff over the Pacific Northwest, where roughly 40% of CONUS generation occurs. These large regional increases may potentially offset some of the significant projected decreases in generation under climate change from facilities that rely on thermal cooling (see [38]). For firm energy, the study indicates the opposite. Over 85% of the 17 pattern scaled GCMs project declines in 5th percentile monthly generation under all scenarios, and in 2050, those reductions are considerably more pronounced under the high emissions scenario. Declines are greatest in the Pacific Northwest due to large projected decreases in summer runoff.

We find that hydropower generation in 2050 increases above the baseline in the REF scenario, yet increases less under the global mitigation scenarios. Despite these smaller generation increases in hydropower generation, the mitigation scenarios show overall net benefits versus the REF scenario because a more rapid rise in electricity prices for the low emission scenarios offsets the slower generation growth. Valuing changes in hydropower generation using

ReEDS electricity prices, the results show that the overall benefits of global GHG mitigation range from $34 billion to $45 billion for Pol3.7 compared to REF, discounted at 3% over the 2015–2050 period. Note that these values do not incorporate the positive effect of mitigation on firm energy generation, which implies higher levels of firm capacity. If firm capacity values were included, the estimated range of mitigation benefits presented here would likely be considerably higher.

Like all current studies on climate change impacts, we are limited by the resolution and confidence levels of simulated climate data from GCMs. Further research would: (1) iterate the water resources systems model with an electric sector planning model such as ReEDS to capture feedbacks between hydropower production, prices, and production from other sources; and (2) improve the calibration of key aspects of water resources systems models, including runoff and demand estimates, hydropower generation, and reservoir operations.

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