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Article, Special Issue "Hydropower 2017"

Impact of a Warming Climate on Hydropower in the Northeast United States: The Untapped Potential of Non-Powered Dams

Nima Ehsani [1,*], Charles J. Vörösmarty [2], Balázs M. Fekete [3] and Eugene Z. Stakhiv [4]

[1] Center for Sustainability, Saint Louis University, Saint Louis, MO, USA; nima.ehsani@slu.edu
[2] Civil Engineering Department, CUNY City College, New York, NY, USA; cvorosmarty@ccny.cuny.edu
[3] Civil Engineering Department, CUNY City College, New York, NY, USA; bfekete@ccny.cuny.edu
[4] Johns Hopkins University, Visiting Scholar, US Army Institute for Water Resources, Alexandria, VA, USA; eugene.z.stakhiv@usace.army.mil
* Correspondence: nima.ehsani@slu.edu; Tel.: +1-347-420-4467

Abstract: A large-scale, high-resolution, fully coupled hydrological/reservoir/hydroelectricity model is used to investigate the impacts of climate change on hydroelectricity generation and hydropower potential of non-powered dams across the Northeast United States megaregion with 11,037 dams and 375 hydroelectric power plants. The model is calibrated and validated using the U.S. Department of Energy records. Annual hydroelectricity generation in the region is 41 Terawatt-hours (Twh). Our estimate of the hydropower potential of non-powered dams adds up to 350 Twh. West Virginia, Virginia, Pennsylvania, and New York have significant potential for generating more hydroelectricity from already existing dams. On the other hand, this potential virtually does not exist for Rhode Island and Delaware and is small for New Jersey and Vermont. Climate change may reduce annual hydropower potential from non-powered dams by up to 13% and reduce current annual hydroelectricity generation by up to 8% annually. Increased rainfall in winters and earlier snowmelt in springs result in an increase in regional water availability in December through March.

 doi:10.20944/preprints201711.0116.v1

In other months, reduced precipitation and increased potential evapotranspiration rates combined with reduced recharge from the shift in spring snowmelt and smaller snowpack result in a decrease in availability of water and thus hydroelectricity generation. This changes call for the recalibration of dam operations and may raise conflict of interests in multipurpose dams.

Keywords: hydropower; climate change; renewable energy; dams

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1. Introduction

To avoid adverse effects of climate change, significant reductions in greenhouse gas emissions should be achieved. Emissions from electricity generation accounted for 31% of the U.S. greenhouse gas emissions in 2013 [1]. The diversity and abundance of U.S. renewable energy resources make deep reductions in electric sector greenhouse gas emissions possible [2]. Using existing commercially available technologies renewable electricity can provide 80 percent of the U.S. electricity by 2050. Nearly 50% of that electricity is expected to come from variable wind and solar photovoltaic generation, 20% from hydroelectricity, and the rest from other renewable sources [3]. Hydropower is the second largest source of electricity after fossil fuels. In 2014, 6% of total electricity generation and 46% of electricity generated from renewables across the U.S. was from hydropower [4].

As the penetration of partially 'dispatchable' wind and solar electricity increases, maintaining electric system reliability and stability becomes more challenging and costly [5]. Plants that can schedule electricity generation as and when required are classified as dispatchable. Fully dispatchable generation units like hydroelectricity plants that can be quickly loaded from zero to their nameplate capacity make good partners for variable wind and solar generation and may be used to minimize the risks and costs of integration of these renewables [6,7].

It is assumed that most of the economically exploitable hydroelectric resources in the U.S. have already been developed [4,8,9]. As a result, while global hydroelectric generation is expected to expand by 31% from 3.65 trillion kWh in 2012 to 5.57 trillion kWh in 2040, hydroelectric generation in the U.S. is expected to expand only by 7% from 0.28 trillion kWh in 2012 to 0.3 trillion kWh in 2040 [4].

Although hydroelectricity is generally considered as clean and renewable, construction of hydropower dams may be socially and politically challenging and affects ecosystems negatively by altering the frequency, duration and timing of peak flows, inundation of the upstream, river fragmentation, disturbing the natural sedimentation flows, and altering water temperatures [10,11]. This does not necessarily need to be the case. Energizing existing non-powered dams utilizes a significant amount of potential energy that is ready to be tapped, without the need to build new dams thus minimizing the adverse social, economic, political and environmental consequences of increasing hydropower generation.

Although the average global impacts of climate change on hydropower resources are expected to be relatively small [5,12], the operation of some hydropower stations may become financially non-viable in the future [13,14]. Solely as a result of climate change, by the 2070s the hydroelectricity production of existing plants in Scandinavia and northern Russia may increase by 15–30%. On the other hand, decreases of 20–50% and more are expected for Portugal, Spain, Ukraine and Bulgaria [15–17]. Hydropower production potential in the Kwanza River, Angola may increase by up to 10% while the hydropower production potential in the Zambezi River Basin may decrease by 28% [18,19]. Potential reductions in the outflow of the Great Lakes can reduce hydropower generation along the St. Lawrence River by 1–17% [15,20].

Climate change can affect hydroelectricity generation in two distinct ways; by altering the magnitude of streamflow and water storage in reservoirs, and by changing the seasonal timing of the peak and low flows [21]. Annual hydropower generation is highly correlated with annual runoff. This reflects the significance of reservoirs for water managers who have to regulate the variability of hydropower generation in extreme wet and dry years [22,23]. In regions where large reservoirs carry over water from one year to another, hydroelectricity generation is more related to multi-year runoff than single-year runoff [24]. Even without changes in annual runoff, variation in seasonal timing of the peak and low flows due to climate warming might increase energy spills from the system due to limited water storage capacities and affect power generation [25]. Warmer temperatures are expected to increase electricity demand for cooling in summers while decreasing the demand for heating in winters. This may alter the annual hydropower pricing patterns and increase the average hydropower prices under climate warming scenarios compared to current and historical climate [26]. The higher electricity price may, in turn, enhance the financial viability of hydropower projects.

In order to make realistic quantitative predictions of regional effects of climate change on hydropower resources, it is necessary to use hydrological models to analyze changes in flow conditions and water levels of dams [5,27].

This study aims to provide an overview of the potential impacts of climate change on the long-term prospects of hydroelectricity in the Northeast United States with a focus on the potential of non-powered dams. 97% of the existing dams in the region do not have hydroelectricity turbines. The latest version of the Water Balance Model (WBM) [28,29] that takes advantage of a general reservoir operation scheme (GROS) [30] to estimate daily discharges from dams is integrated with a hydropower module (Section 4.3). This integrated model is then used to quantify the potential of non-powered dams and also to estimate the potential impacts of different levels of climate warming on hydropower in the northeast using single Global Circulation Model (GCM) and four respective Representative Concentration Pathways (RCPs) [31]. This kind of fully integrated hydrological/reservoir/hydroelectricity model is rarely, if at all, used in high resolution (0.05° lat×long; ca. 4.5 km), regional and global hydropower studies. In fact, we are not aware of any such works. It is not the primary goal of this study to provide detailed results in terms of climate change uncertainties or to forecast absolute hydropower production. The more general subject of interest in the present study is to see if a significant untapped potential for electricity production from non-powered dams exists in the region, and if this potential will still be viable in the future considering the uncertainties that are associated with global climate change. These can then be used to justify the future detailed feasibility and cost-benefit analyses for the expansion of hydropower production in the region.

2. Results

2.1. Model performance

We did not have access to individual generators' records for the hydro dams in the region. However, the monthly state-level electricity generation data since 2001 are available [32], and we used them to calibrate and validate our model. We simulated the daily electricity generation in individual hydropower plants throughout the region and then aggregated the result to calculate the monthly state-level electricity production to be consistent with the data from U.S. Department of Energy (DOE). Comparing the simulation results with reported value for the period of 2001-2010, we calculate the calibration constant α for the hydropower dams in each state. 2011-2015 data were used as the calibration set. Figure 2 compares the monthly reported generated electricity and calibrated simulation results averaged for the calibration and validation period in the Northeast U.S. from 2001 to 2015. The mean error (ME) for the calibration period ads up to -26 Gigawatt hours (Gwh) with an R^2 of 0.98. For the validation period, ME is 42 Gwh with an R^2 of 0.89.

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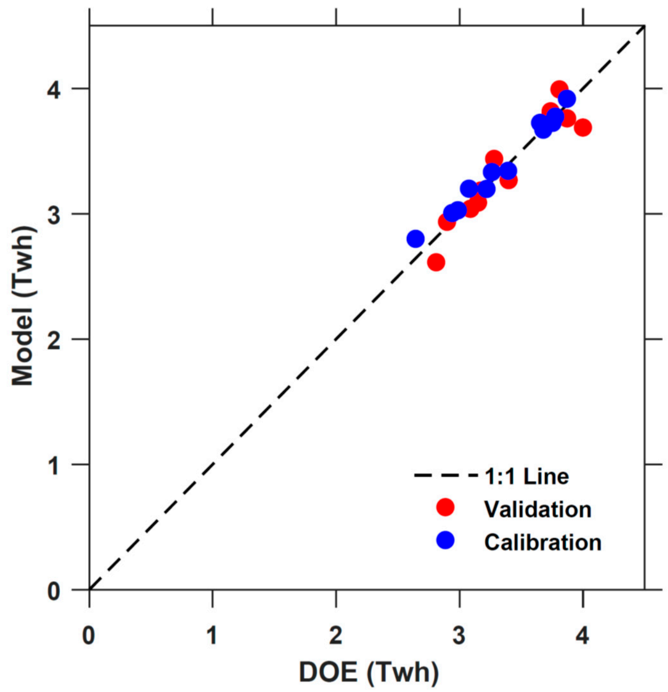
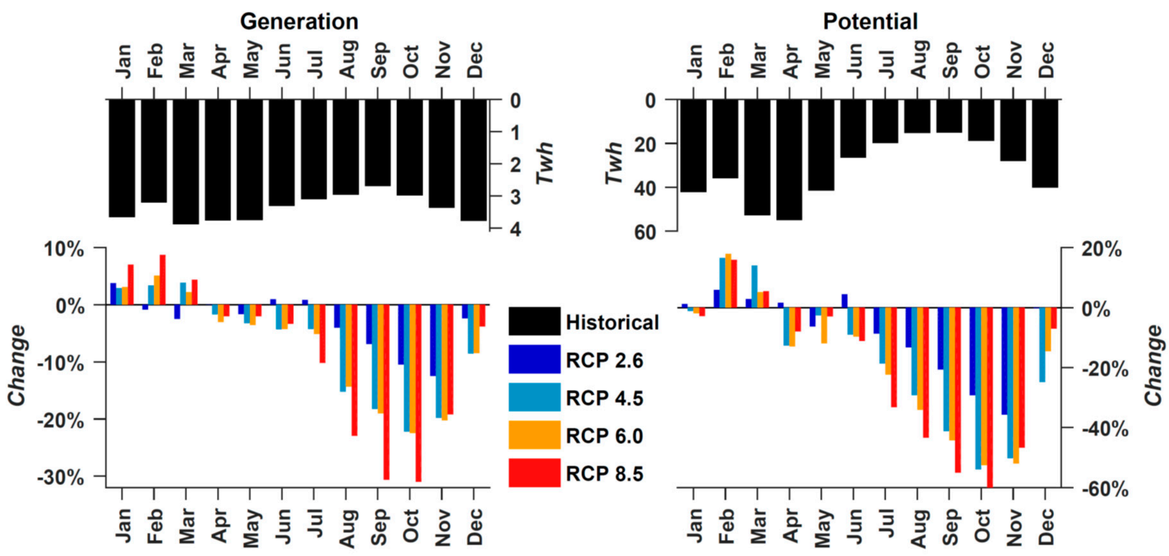


Figure 2. Model performance compared to the Department of Energy reported hydroelectricity generation in the Northeast US. Monthly values are averaged for the calibration (2001-2010) and validation (2011-2015) period.

2.2. Hydropower Potential of non-powered dams and Impact of a Warming Climate on Hydroelectricity Generation

Most of the dams in the Northeast do not have a hydroelectric turbine installed on them. To estimate the hydropower potential of non-powered dams in the region we assumed that all dams in the region have the potential to produce electricity. Figure 3 shows the contemporary hydroelectricity generation and hydropower potential of non-powered dams and the future change caused by climate change. Black bars in Figure 3, show the contemporary (2001-2015) monthly averages and the colored bars show their average changes under the four climate change RCPs for the period of 2080-2099.



126 **Figure 3.** Impact of climate change on developed (left) and potential (right) hydropower in the Northeast U.S. Black bars show the contemporary (2001-2015) average in Terawatt-hours. The colored bars show the potential changes under the four future RCPs for the period of 2080-2099 compared to 2001-2015 averages.

The impact of climate change on hydropower in the region is similar to the pattern of changes in water availability [22]. Increased rainfall and earlier snowmelt are expected to increase the regional water availability in winter. In summer and fall combination of reduced precipitation, increased potential evapotranspiration rates, a shift in spring snowmelt timing and reduced snowpack, result in a decrease in water availability [22]. There will be a slight increase (up to +9%) in average electricity generation in the region in January, February, and March (Figure 3). In every other month, hydroelectricity generation will decrease (by up to -31%). Similar to changes in water availability (streamflows) in the region [22], the maximum monthly increase in average hydroelectricity generation in the Northeast happens in February and maximum decrease in September and October (Figure 3).

Most of the dams in the region have a small effective storage capacity, and their regulatory effects on downstream flows are relatively small [22]. This is the primary reason for a much more substantial seasonal variability in the potential hydropower from non-powered dams compared to the current hydroelectricity generation which is mostly produced by larger dams (Figure 3).

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Reservoirs with larger storage capacities can better accommodate the increased flow seasonality [33]. In addition, maximum daily hydroelectricity generation in existing power plants is limited by their nameplate capacity, but such a limit is not applied to hydropower potential estimates of non-powered dams. The hydropower potential of these smaller dams is also more sensitive to changes in climate as they have a limited capacity to regulate flow and maintain storage levels throughout a year [34]. Many of the non-powered dams are located on smaller streams which are more vulnerable to climate change impacts especially in dry months. Annual potential hydropower from the existing dams in the region is approximately 391 Twh compared to 41 Twh electricity generation from already developed powerplants (Table 1).

The mean annual decline in hydroelectricity generation of the region is 7% for RCP 4.5 and 8% for RCP 8.5 (Table 1). At the state level, (Figure A. 1, Figure A. 2, and Table 1) most substantial declines happen in southern states of the region (WV, VA, MD) which also will be considerably dryer in the future [22]. Figures A. 1 and A. 2 show the impact of climate change on the average monthly hydroelectricity generation and hydropower potential for each state in the region.

Table 1. Impact of Climate Change on Hydroelectricity Generation and Hydropower Potential of Non-Powered Dams in the Northeastern United States. Future projections are based on 2080-2099 averages. Contemporary values are 2001-2015 averages. Negative/positive values for the climate change impact represent the projected change in the future compared to contemporary conditions.

States		CT	DE	MA	MD	ME	NH	NJ	NY	PA	RI	VA	VT	WV	NE Region
Number of Dams		703	83	1426	321	562	634	798	1896	1519	214	2008	356	517	11037
Number of Powered Dams		15	0	25	2	52	35	2	150	16	1	23	44	10	375
Annual Hydroelectricity Generation (Twh)		0.44	0.00	1.02	1.90	3.68	1.42	0.02	25.59	2.56	0.00	1.27	1.22	1.36	40.49
	RCP 4.5	-9%	0%	-4%	-15%	-6%	-8%	1%	-5%	-9%	0%	-18%	-8%	-11%	-7%

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Climate Change Impact	RCP 8.5	-10%	0%	-6%	-19%	-11%	-13%	0%	-4%	-9%	0%	-26%	-10%	-18%	-8%
Annual Potential Hydropower (Twh)		14.07	0.22	12.68	8.41	14.86	8.42	2.92	104.68	72.38	0.33	43.51	3.90	104.51	390.88
Possible Hydroelectricity Increase		3074%	NAN*	1140%	344%	304%	493%	12138%	309%	2726%	NAN*	3323%	221%	7562%	865%
Climate Change Impact	RCP 4.5	-2%	0%	-2%	-15%	0%	-4%	-1%	-2%	-11%	3%	-31%	-4%	-20%	-12%
	RCP 8.5	-3%	2%	-4%	-18%	1%	-7%	-1%	3%	-13%	4%	-35%	-6%	-25%	-13%

* The Possible Hydroelectricity Increase is calculated based on Annual Hydroelectricity Generation. Because current Annual Hydroelectricity Generation (denominator) in RI and DE is zero, the mathematical calculation for the Possible Hydroelectricity Increase is a NAN value.

3. Discussion

Hydroelectricity has a more uniform generation rate compared to the wind and solar electricity. In addition to diurnal fluctuations solar and wind-generated electricity in the region has a highly seasonal nature (Figure 1). Based on the data from past recent years, monthly hydroelectricity generation in the Northeast US is always above 70% of its peak generation throughout the year [32]. Although, this may change in the future.

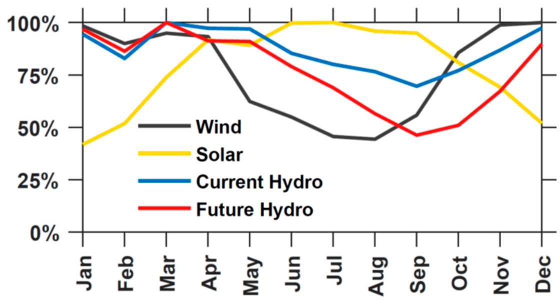

Figure 4. Seasonality of wind, solar and hydroelectricity generation in the Northeast United States. Current Hydro is based on 2001-2015 DOE data. Future Hydro is based on HadGEM2-ES RCP 8.5 simulations for 2080-2099. 100% shows the month with peak electricity generation. Anything less than 100% means that the system performance in that month is below installed capacity.

In general, the average global impacts of climate change on hydropower resources are expected to be relatively small [5,12], and some studies suggest other sources of uncertainty like electricity prices may, in fact, be far more critical than runoff (climate change) uncertainty [35]. Shorter freezing season, earlier snowmelt and larger evapotranspiration rates combined with changes in precipitation patterns due to climate warming increase water availability in winters and reduce it in warm and dry months in the Northeast United States [22]. Given the projected shift in hydrological conditions, water resource managers may need to reconsider the trade-offs between having a flood and drought-resilient system, electricity generation, and meeting downstream water demands as they compete to utilize the same limited reservoir storage [22,36]. The expected shift in peak streamflows from early spring to late winter might have significant effects on power generation and revenues [26].

We are estimating 8% decrease in annual hydroelectricity generation in the Northeast U.S. based on HadGEM2-ES RCP 8.5 scenario for the period of 2080-2099 compared to 2001-2015 average. Monthly and state level calculations show a much larger range of change. For example, hydroelectricity generation in New Hampshire may increase more than 30% in February and decrease by 60% in October (Figure A 1). Northern states like Maine, New Hampshire, and Vermont are projected to experience an increase in January, February, and March while southern states like Virginia and West Virginia are projected to produce less electricity from hydropower in the same months. Hydroelectricity generations are expected to decrease everywhere in the region in summer and fall (Figure A 1).

Adaptation of new and optimized reservoir operations can partially mitigate the adverse effect of climate change by reducing the loss of hydroelectricity generation [22,37]. Hydroelectric dams have limited storage and generation capacity that limits their ability to mitigate changes in the timing and magnitude of high flows which results in an increase in energy spill from the system. Increasing the hydroelectricity generation capacity (more/larger turbines) can reduce energy spills and increase revenues [38]. Inadequate water storage capacity increases the vulnerabilities of water and hydroelectric systems to hydrologic impacts of climate change [38–42]. Systems with limited water storage capacities cannot take full advantage of increased streamflows [25]. Another way to reduce energy spills is to store the excess energy of high winter flows in reservoirs to be used in dry summer months (increasing storage capacity) [22].

Energizing existing non-powered dams can be a sustainable way of implementing and operating hydropower dams to optimize the production of renewable electricity without the negative consequences of the construction of more dams. We estimated (Table 1) that the hydropower potential from the non-powered dams in the region is more than eight times larger than the current hydroelectricity production in the region (350 Twh vs. 41 Twh); and also much larger than other similar estimates [43–45]. A 12% utilization of this untapped potential will double the hydroelectricity generation in the region without the need for construction of new dams. It is important to remember that no other study (to our knowledge) has used this level of detail and a fully coupled hydrological/reservoir/hydroelectricity model for this type of analysis.

Levelized cost of electricity (LCOE) is often cited as a convenient summary measure of the overall competitiveness of different generating technologies [46]. Based on U.S. Energy Information Administration estimates of Levelized Cost of Electricity (LCOE) [46], hydroelectric resources have a competitive advantage compared to other renewable resources (without including the targeted federal tax credits) (Table 2). This is especially important for the development of the non-powered dams because a large part of the capital cost for new generation resources is the civil and structural costs of the project. So the LCOE will be substantially smaller as the dam/reservoir already exists. Although detailed analysis for individual dams is necessary, considering there are more than ten thousand non-powered dams in the region, chances are energizing many of these existing dams is financially superior to developing other sources of energy, both renewable and non-renewables.

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Table 2. Estimated Levelized Cost Of Electricity (LCOE) for new generation resources, for plants entering service in 2022 [46].

U.S. Average LCOE (2016 $/MWh)for Plants Entering Service in 2022				
Plant Type	**Capital Cost**	**Fixed and Variable O&M[1]**	**Transmission Investment**	**Total System LCOE**
Coal 30% with carbon sequestration	94.9	43.9	1.2	140.0
Advanced Gas Combustion Turbine	25.9	65.3	3.5	94.7
Advanced Nuclear	73.6	24.3	1.1	99.1
Geothermal	32.2	12.8	1.5	46.5
Biomass	44.7	56.4	1.3	102.4
Wind-Onshore	47.2	13.7	2.8	63.7
Wind-Offshore	133.0	19.6	4.8	157.4
Solar PV	70.2	10.5	4.4	85.0
Solar Thermal	191.9	44.0	6.1	242.0
Hydroelectric	56.2	8.2	1.8	66.2

[1] O&M = Operations and maintenance.

4. Materials and Methods

4.1. Hydroelectricity in the Northeast United States

Geographical domain of this study is the northeast region of the United States and expands from Virginia in the south to Maine in the north and includes 13 states and District of Columbia. There are 11037 georeferenced dams in the region with total storage capacity of 71.5 km^3 [47]. Only 375 of these dams are producing hydroelectricity [48]. Table 1 shows the total number of dams, dams with hydropower generators, and the annual hydroelectricity production in each state.

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Average annual hydroelectricity generation in the Northeast is approximately 41 Terawatt-hours (Twh) (Table 1) which constitutes 62% of electricity from all renewable resources and 6% of total electricity production in the region [32]. State of New York has the largest number of powered dams and is the leading producer of hydroelectricity in the region. Delaware does not produce electricity from hydropower and hydroelectricity generation in Rhode Island is negligible.

In a report that assesses the feasibility of hydroelectricity generation from new low-power and small hydropower plants in the United States, Hall et al. [45] estimated that Northeast could potentially increase its hydroelectricity generation capacity by 85% (34 Twh). In another report that assessed the energy potential at non-powered dams in the United States, Hadjerioua et al. [43,44] estimate that by adding hydroelectricity turbines to the non-powered dam hydroelectricity generation in the northeast can be increased by 34% (14 Twh).

4.2. Hydrological modeling

The latest version of the Water Balance Model (WBM_{plus}) [29] fully coupled with a General Reservoir Operation Scheme (GROS) [30] and a hydroelectricity module (section 2.3) was used to estimate the hydropower potential of the non-powered dams and also the impacts of different levels of climate warming on hydroelectricity generation in the Northeast United States. WBM_{plus} [28,29,49] is a daily, grid-based macroscale hydrology model which uses a simple routing scheme employing the Muskingum-Cunge method to solve the St. Venant equations [50] to propagate simulated runoff along a simulated topological river network. GROS [22,30] is a reservoir operation module that represents the daily operation of dams in the region [30]. This reservoir module is completely integrated within WBM_{plus} and represents the cumulative regional hydrological effect of dams on the regulation of downstream flows. GROS is a dynamic daily reservoir operation module that adapts to changes in climate and automatically adjusts the operation of dams based on the reservoir water storage level, timing, and magnitude of incoming river flow.

To quantify the potential impacts of different levels of climate warming on hydroelectricity generation and hydropower potential of the Northeast by using "the minimal setting" scenario of the Inter-Sectoral Impact Model Intercomparison Project (ISI–MIP) [51,52]. The minimal setting was chosen to span both the GCM and the RCPs space to a basic extent and comprises all four RCPs for one global climate model (HadGEM2-ES [53]).

Hydrological calculations are carried out at a resolution of 0.05° (lat×long; ca. 4.5 km) and in daily time steps. In a separate publication, we have provided a detailed overview of the effects of different levels of climate warming on water resources of the Northeast with a focus on the role of dams [22]. We showed that the combined effects of warmer temperatures, shorter freezing season, earlier snowmelt, larger evapotranspiration rates, and changes in precipitation patterns increase water availability in winters and reduce the availability of water in warm and dry months in the Northeast United States. The timing of the most water-scarce month of year shifts to one month later while the most water-rich month of year in the region shifts to one month earlier [22]. We also showed that the impact of dams on downstream flows would be amplified and their importance in providing water security will increase. The hydrological implications of a warmer climate can affect the ability of the region to meet hydropower production targets as well as human and environmental water demand [22,25].

4.3. Hydroelectricity Module

$P=\alpha\varrho Qgh$ estimates hydropower generation from a reservoir in our model. Where P is in Watts, ϱ is water density (1000 $kg.m^{-3}$), Q is flow rate ($m^3.s^{-1}$), g is acceleration due to gravity (9.78 $m.s^{-2}$), and h is water head of the turbine (m). α is a constant usually used to represent the efficiency of turbines. In this work, we are using α as our calibration constant.

Flow rate (Q) is equal to release from the dam which is calculated in GROS. Water head (h) is equal to water level behind the dam and is calculated as:

$$h = \sqrt[9.8]{\frac{S}{C}} \quad (1)$$

$$C = \frac{S_{max}}{H_{max}^{9.8}}$$

h represents the water head (m), and S is the water storage level in any day (m^3). Maximum storage capacity of dams (S_{max}) and their maximum height (H_{max}) are available from National Inventory of Dams [47]. These equations are based on analysis of 7936 reservoirs in the world to investigate the relationship between reservoir inundation and storage in hydroelectricity dams [54].

Power (P) is linearly related to Flow and head. However, because water head (h) is related to storage (S) by a power of $\frac{1}{9.8}$, changes in the magnitude of flow have a much larger impact on hydroelectricity production compared to changes in the volume of water that is stored behind the dams. Thus, hydroelectricity production is more sensitive to changes in magnitudes of flow than to water storage volumes of dams [25].

Acknowledgments: This work was supported by the National Science Foundation, Award No. 1049181.

Author Contributions: For research articles with several authors, a short paragraph specifying their individual contributions must be provided. The following statements should be used "X.X. and Y.Y. conceived and designed the experiments; X.X. performed the experiments; X.X. and Y.Y. analyzed the data; W.W. contributed reagents/materials/analysis tools; Y.Y. wrote the paper." Authorship must be limited to those who have contributed substantially to the work reported.

Conflicts of Interest: The authors declare no conflict of interest. The founding sponsors had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript, and in the decision to publish the results.

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Appendix A

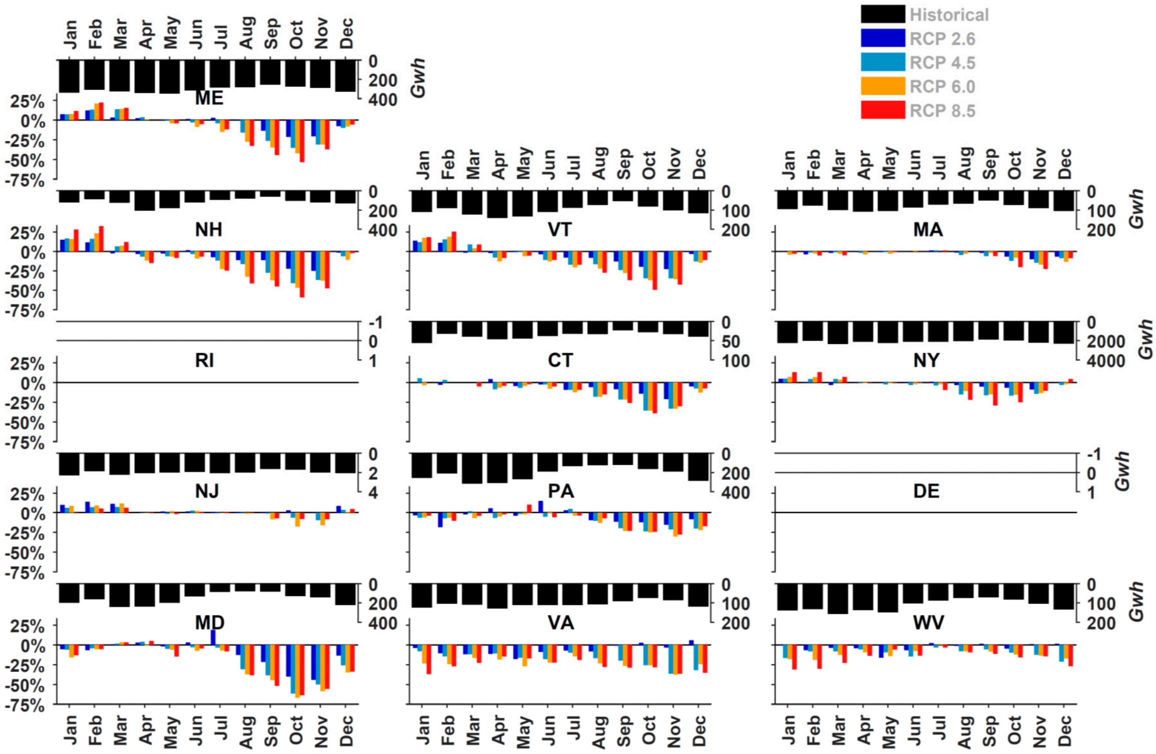

Figure A 1. Impact of climate change on hydroelectricity generation from the existing power plants in each state in the Northeast USA. Black bars show the average electricity generation in 2001-2015 in Gigawatt-hours. The colored bars show the change in hydroelectricity production under the four climate change RCPs for the period of 2080-2099 compared to 2001-2015 averages.

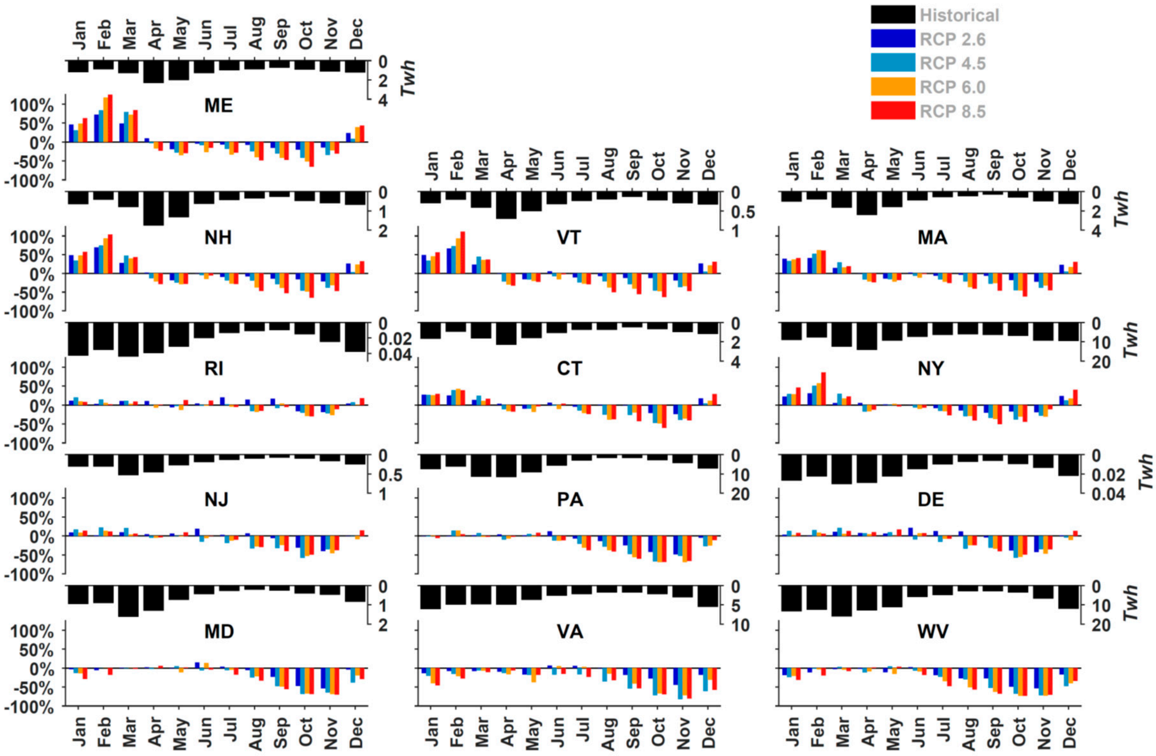

Figure A 2. Impact of climate change on hydropower potential for each state in the Northeast USA. Black bars show the average for 2001-2015 in Terawatt-hours. The colored bars show the change in hydropower potential under the four climate change RCPs for the period of 2080-2099 compared to 2001-2015 averages.

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