

## ABSTRACT

Title of Dissertation: WATER-ENERGY-CLIMATE NEXUS:  
INTERDEPENDANCIES AND TRADEOFFS,  
AND IMPLICATIONS FOR STRATEGIC  
RESOURCE PLANNING

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The water-energy nexus has been an active area of research in recent decades and has been explored in many different directions pertaining to its core. It is imperative to manage water and energy in a holistic approach as there are critical interconnections between the two systems. Climate change is an intrinsic environmental variable that has vital implications for the study of water-energy nexus, and hence, the term water-energy-climate nexus is used throughout the dissertation in reference to the interdependencies and tradeoffs between these systems. This dissertation is composed of three research studies under the domain of the water-energy-climate nexus, and they are interconnected through the intrinsic linkages among the three systems.

The first study deals with the vulnerability of U.S. thermoelectric power plants to climate change. Findings suggest that the impact of climate change is lower

than in previous estimates due to the inclusion of a spatially-disaggregated representation of environmental regulations and provisional variances that temporarily relieve power plants from permit requirements. This study highlights the significance of accounting for legal constructs and underscores the effects of provisional variances along with environmental requirements.

The second study demonstrates the adaptation measures taken by the U.S. energy system in the face of constraints on water availability. Results show that water availability constraints may cause substantial capital stock turnover and result in non-negligible economic costs for the western U.S. This work emphasizes the need to integrate water availability constraints into electricity capacity planning and highlights the state-level challenges to facilitate regional strategic resource planning.

The last study assesses the potential of surface reservoir expansion for major river basins around the world as an adaption measure to secure a reliable water supply. Results suggest that conservation zones and future human migration will have a substantial, heterogeneous impact on the maximum amount of reservoir storage that can be expanded worldwide. Findings from this study highlight the importance of incorporating human development, land-use activities, and climate change drivers when quantifying available surface water yields and reservoir expansion potential.

This dissertation takes an integrated holistic approach to examine water and energy system interrelationships, and assesses the role of climate change in reshaping the interconnectivity. The three studies are tied in to each other by identifying some of the challenges the society is facing in the water-energy-climate nexus (first study) and providing a few possible solutions in both energy supply (second study) and

water supply (third study) sector. Novelty of this dissertation includes but not limited to 1) explicit representation of state-level environmental regulations pertaining to power plant operations in the U.S. 2) integrated approach that captures the interactions of energy system with other sectors of the economy; and 3) global assessment of reservoir capacity expansion potential with consideration of multiple constraints. General conclusions, along with further details, provide insights for sustainable resource planning and future research directions.

WATER-ENERGY-CLIMATE NEXUS: INTERDEPENDANCIES AND  
TRADEOFFS, AND IMPLICATIONS FOR STRATEGIC RESOURCE PLANNING

by

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## Preface

Five years and three months. That's how long I've spent of my 20s in the state of Maryland.

When I first came to work at the Joint Global Change Research Institute (JGCRI) as a fresh graduate from Oklahoma, where I spent four years with familiar surroundings, I was completely overwhelmed. I was away from my family and friends, away from the convenient communities, and away from everything that I'm already attached to. However, as scary as this new chapter in my life was, I knew I would not give up, because I wanted something bigger for myself. Not knowing what was ahead, I made the decision to step outside my comfort zone and begin a new journey in a completely strange place. From the first day I landed in Baltimore-Washington International Airport to the day I finalized my defense date, I have experienced many ups and downs that led to where I am today. I cannot recall how many times I cried myself to sleep from homesickness and stress, but never a single day went by that I regretted my decision. Knowing I have my family behind me and wanted to see me make it to the finish line, is what kept me going during those hard times.

At JGCRI, I was fortunate to be working side by side with scientists who showed me the value of socially relevant research and I witnessed many groundbreaking moments that made a real impact on society. This invaluable working experience clarified my chosen career path, and solidified my decision to go back to school and pursue a doctoral degree. Throughout the Ph.D. program, I had the

privilege to be financially supported by JGCRI so that I could focus entirely on my research and not worry about the next paycheck.

I owe my highest gratitude to my two mentors, whom will have a long lasting positive impact on my life. Dr. Mohamad Hejazi, who first took me in as his post-master research associate, completely changed my perception of research and revealed self-potential that I didn't even know existed. He challenged me to think deeper and explore further. The completion of this dissertation was clearly not possible without his foresights and devotions. One especially noteworthy thing that Dr. Hejazi has unintentionally taught me, were many idioms and proverbs during our daily communications. “Tip of an iceberg”, “low hanging fruit”, “elephant in the room”, and “my two cents”, just to name a few. He may not know this but I felt more confidence communicating with other people by occasionally dropping in a few proverbs I learned from him.

Dr. Barton Forman, my Ph.D. advisor at University of Maryland, is another mentor I owe my highest gratitude to. Not knowing me or JGCRI well, he courageously took me in as his Ph.D. student and patiently helped me get up to speed in the program. He was the most attentive advisor I could have ever asked for. He made sure that he was available for every request and concern I had, and provided all the resources and opportunities needed to help further my academic career development. Over the three years of being in his research group, I've learned important skills of science and communication, and developed new perspectives on the implications of my studies. He introduced me to a vast diversity of scientific

research and helped me appreciate the nuances of pioneering research that drives this society.

I would also like to thank Dr. Leon Clarke, Dr. Jae Edmonds, Dr. Gokul Iyer, Dr. Yuyu Zhou, Dr. Xuesong Zhang, Dr. Gerald Galloway, the entire JGCRI team and my officemates at UMD. They compose a crucial part of my life in Maryland and have contributed directly or indirectly to the completion of this dissertation. It is noteworthy that Dr. Gokul Iyer's success after obtaining a Ph.D. degree from Maryland set up a very high bar to for me to reach. I would also like to thank the administrative staff at both JGCRI and UMD for putting up with me and answering all my questions. I need to thank all the people who created a good atmosphere in the work place.

Furthermore, I would like to acknowledge three UMD committee members: Dr. Richard McCuen, who taught me the value of work ethic and challenged me to maximize my potential; Dr. Nathan Hultman, who graciously let me join his research team and opened my mind to many new ideas and fields; Dr. Kaye Brubaker, who was very beneficial in crafting my dissertation proposal and I believed I learned from the best.

Dr. Haewon McJeon and Dr. Minji Jeong are two of my very special friends, of who I feel so lucky to have crossed my paths with. It may seem odd to others, but Dr. Haewon McJeon's quirky characters and peculiar perspectives about this world helped me overcome many setbacks and obstacles in my life. His life hacking techniques saved me, countless times, from difficult situations in work and in life. Dr. Minji Jeong, my roommate for four years, was my inspiration for many things. We



used to talk about everything at dinner table, sip teas together in a cozy afternoon, comfort each other during difficult times, and share happy moments that shed light into our lives. She was the best roommate I could ever ask for and she will always be a big sister I look up to. To Lucas and Larry, you two have been through everything with me from day one. You are always by my side when I am down. You guys are the best pets in the world! To all my friends, thank you for your understanding and encouragement in my moments of crisis. Meg Ryan, Jing Wang, Pan He, the list goes on and on. I cannot list all the names here, but your friendship makes my life a wonderful experience.

Last but not least, I owe my utmost gratitude to my parents and my husband. They are the ones who encouraged me to pursue my dreams and always believed in me when I had cold feet. My parents gave me all they could so that I could receive the best education in China. Their devotions earned me the life-changing opportunity to study in the U.S. All their support over the years was the greatest gift anyone can possess. My husband, Dr. Guangzhe Yu, is far more than my partner in life. He is my mentor, my advocate, and my harbor. If I wrote down everything I ever wanted in a husband and best friend, I would not have believed I could meet someone better! Thank you for walking this journey together with me. You are behind every triumph I achieve.

## Dedication

This dissertation is dedicated to my parents and my husband who gave me strength to reach for the stars and helped me in all things great and small. This is for my beloved family.

仅以此文献给我亲爱的家人 — 我的父母和我的先生。是他们在读博的道路上一直鼓励我支持我，帮助我实现自己的梦想。没有他们就没有这篇博士论文的诞生。

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Part of the third study was developed during the Young Scientists Summer Program at the International Institute for Applied Systems Analysis (IIASA), with financial support from the IIASA Annual Fund. I would like to acknowledge the Coupled Model Intercomparison Project Phase 5 (CMIP5) and the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) for providing the climate and hydrological data. I would also like to thank Dr. Nils Johnson for his input during the early formulations of this research.

I would like to show my gratitude to the journal *Nature Energy* for publishing the first study on their 2017 July issue, volume 2. The full citation of this paper is: Liu L., M. Hejazi, H. Li, B. Forman, and X. Zhang (2017), Vulnerability of US thermoelectric power generation to climate change when incorporating state-level environmental regulations, 2, 17109, *Nature Energy*. DOI: 10.1038/nenergy.2017.109.

The second study is currently under review by *Nature Sustainability* and the third study is under review by *Environmental Research Letters*.

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# Chapter 1 Introduction

## 1.1 Overview of Water-Energy-Climate Nexus

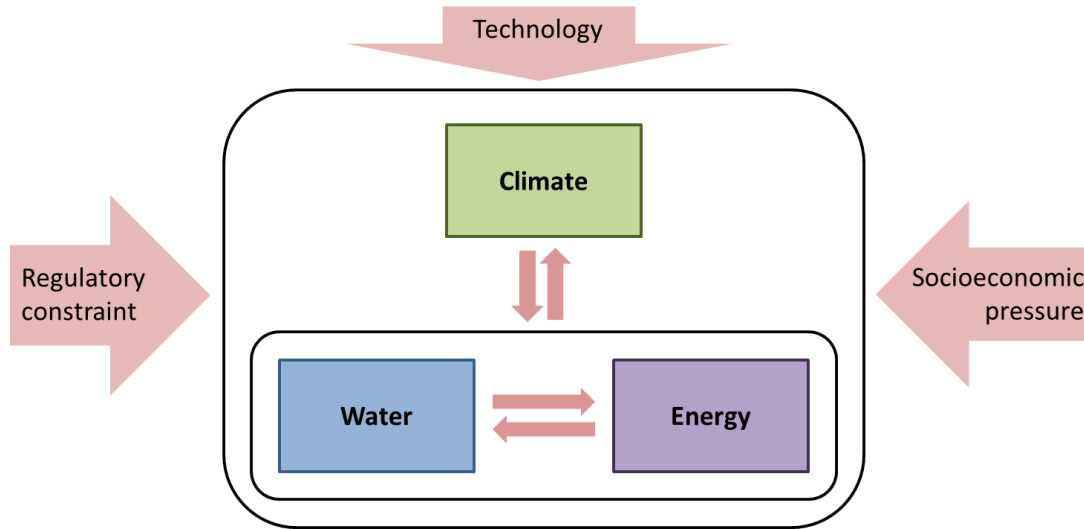
Water and energy are the worlds' two most critical resources<sup>1</sup>. Both resources have their own significant role in society, but it is often less recognized that water and energy are interdependently connected through physical processes. Water is required for thermoelectric production in the process of cooling and steam generation. In the U.S., approximately 38% of the total freshwater withdrawal is attributed to the electricity sector<sup>2</sup>. Globally, this portion of water is about 14%<sup>3</sup>. Energy is also needed to supply, treat, and deliver water to end users. Approximately 1.2% – 1.8% of total U.S. primary energy consumption is attributed to conveyance, water purification, water distribution, and wastewater treatment<sup>4</sup>. Energy and water systems are tightly linked, and changes in either system would have propagating effect on the other. Feedbacks between systems can be further exacerbated under anticipated climate change.

Climate, being the intrinsic forcing to the global hydrological cycle, affects hydrologic variability at various spatial and temporal scales<sup>5-7</sup>. Climate conditions inevitably impact local energy consumption, particularly to indoor cooling and heating<sup>8</sup>. At the same time, processes in water and energy systems can modify climate on a large scale over long period through thermodynamic processes<sup>9,10</sup>. A more apparent example of this phenomenon is how greenhouse gases emitted from burning fossil fuels, have been increasing the global mean air temperature. The climate

system, therefore, can be considered an external environmental factor over the water-energy interdependencies, of which also exert feedback back to the climate system.

There is no formal definition for the water-energy-climate nexus, but the concept refers to the interdependencies, interactions and tradeoffs between water, energy and climate systems. These intrinsic linkages are integral to social and economic development. In the past, energy and water systems have been developed, managed, and regulated independently and without significant acknowledgement of the connections between them<sup>11</sup>. This leads to conflicting demand for one another during critical times (e.g., drought, heatwaves, flooding and so on), and increases stress on the already aging energy and water infrastructure<sup>11–13</sup>.

The conventional approach to manage water and energy systems separately can no longer sustain the mounting demand for these two dependent resources, which are further challenged by population growth, economic development, technological innovations, policy incentives and climate change. An integrated and holistic way of thinking about water and energy, therefore, is needed to tackle some of the urging issues at the heart of the water-energy-climate nexus. A simple schematic diagram is illustrated in Figure 1-1 that shows the interactions among water, energy, and climate systems. External pressures on the water-energy-climate system include socioeconomic development (e.g., GDP, population), technological improvements and regulatory constraints. Much research has been done to investigate the intricate interactions between each individual component. Yet, interconnections between systems at policy-relevant geospatial scale (e.g., national, subnational and provincial) are subject to more extensive investigations.



*Figure 1-1 Water-Energy-Climate nexus diagram*

## 1.2 Key Research Questions

This dissertation focuses on one specific direction of interconnection between systems, that is, water for energy, and dives into three distinctive but related studies that provide a comprehensive assessment of energy's dependency on water resources. This dissertation specifically targets three aspects pertaining to water for energy: 1) energy system's vulnerability to an external environment, 2) adaptation measures in the energy supply sector; and 3) adaptation measures in the water supply sector. The dissertation is aimed to address three key research questions pertaining to these three aspects.

### 1. Scope of problem

*How vulnerable is the current U.S. thermoelectric power generation system to changes in climate?*

- What is the impact of climate change on thermoelectric power plants?

- What role do environmental regulations play on power plant vulnerability?

## 2. Adaptation in energy supply

*How is the U.S. electricity system going to adapt to constraints on water availability?*

- How will the U.S. electricity supply portfolio (e.g., fuel mix and technology portfolio) evolve with considerations of water constraints at the state level?
- What are the policy implications for future U.S. electricity capacity planning?

## 3. Adaptation in water supply

*What is the surface water reservoir expansion potential for major hydrologic basins around the world?*

- What are the impacts of competing land-use activities and environmental flow constraints on the potential for expanded reservoir capacity needed to secure freshwater yields?
- Where are policies and infrastructure investments needed to sustain and improve global water security?

### **1.3 Literature Review**

There are vast number of studies on water-energy system interactions, with focuses on different side of problems and scale of issues. Solving the conflicts between energy and water systems require adaptations in both demand and supply side of energy and water sectors. A number of studies have investigated the

implications of changing water or energy demand on water-energy system interactions<sup>14,15</sup> and the role of climate change in affecting energy and demand<sup>16–18</sup>. As this dissertation does not provide analysis on climate change impact on water and energy demand or adaptation strategies in demand side of energy and water sector, general literature relevant to supply side of energy and water sector is reviewed and discussed hereinafter. More in-depth literature review for each study is provided in Chapter 2-4.

Extensive research has been done to assess the vulnerability of the electricity supply sector to climate change<sup>19–25</sup>. Previous studies suggest that thermoelectric power generation is vulnerable to climate change owing to the combined effects of lower summer river flows, higher water temperatures, and regulatory enforcement. Such adverse impacts could be further exacerbated as climate change progresses<sup>20,23,25</sup>. However, studies based on historical data suggest different outcomes whereby the level of impact is expected to be less severe than what modeling results indicate. The differences between the studies are largely due to operation optimization, provisional variances approval and co-management of power plants<sup>19,22,26</sup>. **The first study in this dissertation thus resolves the conflicting outcomes from the two types of studies, and provides a comprehensive assessment of the vulnerability of the electricity sector to climate change in the U.S.**

As water resources are shared by end users other than just electricity generators, water availability in the natural system, and its allocation to end users, can result in different levels of water stress faced by the electricity sector depending on location. The different water resource abundance and allocation practices in the U.S.



may lead to very different adaptation strategies in electricity capacity expansion across regions. There are not many studies assessing the implications of water constraints on U.S. electricity generation and the existing ones are limited in terms of scale and robustness<sup>27–29</sup>. Water availability to electricity generation is overestimated in existing studies<sup>27,28</sup>, which results in biased output and can underestimate the impacts of water constraints on the energy system. In addition, end-user electricity demand is exogenously assumed in all existing studies, and thus, electricity supply-demand dynamics are not well captured or reflected in electricity capacity expansion<sup>27–29</sup>. **The second study in this dissertation thus extends previous work by properly representing water constraints and integrating both supply and demand effects under a consistent framework.**

As water resources become scarce in some regions around the world and water availability has become a limiting factor in socioeconomic development, securing water supply via expanding reservoir capacity is considered an adaptation strategy to help balance rising water demand with long-term water availability. Previous analyses on global reservoir storage focused on existing storage capacities and did not account for the effect of climate change, land-uses, human development and environmental flow regulations on reservoir expansion<sup>5,30,31</sup>. **The third paper in this dissertation thus conducts initial investigation to quantify reservoir storage expansion potential at global scale, and considers multiple limiting factors that constraint basin-scale reservoir expansion.**

## **1.4 Dissertation Structure**

This dissertation proceeds as follows. Chapter 1 provides a broad overview of the water-energy-climate nexus topic and describes the overarching research questions addressed by this Ph.D. dissertation. Chapters 2-4 describe each of the three studies that specifically answer each of the three posed research questions. Findings of these three studies have been published in peer-reviewed journals or are under journal peer review, as of the date this dissertation was completed. Relevant supplementary materials are shown in Appendices, with cross references in the corresponding text. Finally, concluding remarks are provided at the end, summarize overall findings from this dissertation and offer the author's thoughts on future explorations.

## Chapter 2 Vulnerability of Thermoelectric Power Generation in the U.S. to Climate Change when Incorporating State-level Environmental Regulations

*This chapter was published in Nature Energy. Full citation is as below:*

*Liu L., M. Hejazi, H. Li, B. Forman, and X. Zhang (2017), Vulnerability of US thermoelectric power generation to climate change when incorporating state-level environmental regulations, 2, 17109, Nature Energy. DOI:10.1038/nenergy.2017.109*

### **2.1 Introduction**

#### 2.1.1 Rationale

Two-thirds of total U.S. electricity generation requires water for cooling, and two-fifths of the total U.S. freshwater withdrawal is required for thermoelectric production<sup>2,32</sup>. Extreme weather events are the leading cause for disruptions to the electricity sector in the U.S., and incidents of power plant shut-downs or curtailed operations due to extreme events (e.g., water shortages) have become more frequent in recent years<sup>12,33</sup>. Growing demands for power and water, combined with increasing frequency of extremes due to climate change are likely to jeopardize the reliability of the US thermoelectric sector in the future<sup>29,34</sup>.

#### 2.1.2 Literature Review

The extent and intensity of climate change impacts on thermoelectric generation have been widely discussed in recent literature<sup>19–23,25,26,35–37</sup>. There are

typically two different approaches to assessing the role of climate change on thermoelectric generation – integrated modeling and historical data analysis. Modeling studies suggest that thermoelectric power generation is vulnerable to climate change owing to the combined effects of lower summer river flows, higher water temperatures, and regulatory enforcement. van Vliet et al.<sup>20</sup> presented the vulnerability of thermoelectric power generation in Europe and the United States to future climate change. The study concluded that 4.4%-16% of the generation capacity in the U.S. will be lost by the mid-21<sup>st</sup> century. Bartos and Chester<sup>23</sup> focused predominantly on recirculating power plants in the Western U.S. and found that climate change could reduce generating capacity during the summer by 1%-3% with reductions up to 7%–9% under a ten-year drought scenario. Miara and Vörösmarty<sup>22</sup> showed that current environmental regulations may reduce power production in their conceptual framework in the northeastern U.S., but can improve the net electricity output from multiple plants when co-managed optimally. van Vliet et al.<sup>25</sup> presented a global assessment of the vulnerability of energy generation systems and suggested that 7%-12% of thermoelectric power capacity will be lost in North America by the 2050s if no adaptation strategies were adopted.

Studies based on historical data suggest different outcomes whereby the level of impact is expected to be less severe than indicated by modeling results<sup>19,26</sup>. The differences between the two approaches are largely due to the treatment of operation optimization, provisional variances approval and co-management of power plants. Greis et al.<sup>19</sup> concluded that a reduction of thermoelectric output is more apparent in the summer than in the winter or spring, but that reductions in output associated with

increases in average air and water temperatures only result in 0.1%-0.2% of changes in gross electrical output by 2050. Henry and Pratson<sup>26</sup> examined 39 open- and closed-loop coal and natural gas power plants in the U.S., and concluded that thermoelectric plants, particularly closed-loop plants, are much less susceptible to temperature changes than previously expected. The alleviating factors are predominantly due to the optimization of plant operations and provisional variance approvals. Both Madden et al.<sup>21</sup> and Henry and Pratson<sup>26</sup> found that more than half of all evaporative cooling systems in the U.S. report maximum temperature discharges that exceed the regulated threshold temperature.

Current modeling studies typically consider one or more of the following impacts on thermoelectric power plants: efficiency loss due to ambient temperature fluctuations; water availability constraints on evaporative cooling systems; and regulatory constraints on thermal effluent. The last binding factor is somewhat ambiguously interpreted between different studies. For example, van Vliet et al.<sup>20</sup>, Madden et al.<sup>21</sup>, Bartos and Chester<sup>23</sup>, and van Vliet et al.<sup>25</sup> investigated the compliance of stream temperature at the discharge outlet with regulations rather than the stream temperature in the mixing zone. Miara and Vörösmarty<sup>22</sup> adopted the latter interpretation assuming an immediate equilibrium of temperature in the mixing zone. The majority of these studies assumed a fixed value for the temperature threshold across regions, except for the case of Madden et al.<sup>21</sup> where different thresholds were identified for 15 U.S. states.

### 2.1.3 Objectives

To date, essentially all modeling exercises assume no spatial heterogeneity in regulation of water temperature threshold (normally 32°C) for thermal effluent from power plants. This assumption is problematic because it lacks true representation of legal constructs in which the operation of power plants are managed, and it also ignores the alleviating effect provided by provisional variances which are regularly granted during extreme conditions. In this study, we employ a modeling framework that accounts for climate change and state-level regulatory impacts on thermoelectric power generation in the U.S. We use a state-of-the-art regional Earth system model to represent local and regional hydrologic conditions. Representation of thermoelectric power plants in our framework expands on the work of Miara and Vörösmarty<sup>22</sup>, which is established for a conceptual power plant. We explicitly included the U.S. state-level environmental regulations on thermal effluents, as well as relieving mechanisms (provisional variances) to better reproduce historical thermoelectric output (Appendix A Supplementary Note 1, 2 and Supplementary Table A-4). This study quantifies the impact of future climate change in the context of current environmental regulations and compliance contingencies; we find that climate change alone has a small direct impact on thermoelectric generation in the U.S., unlike other modeling studies where the impact tends to be larger.

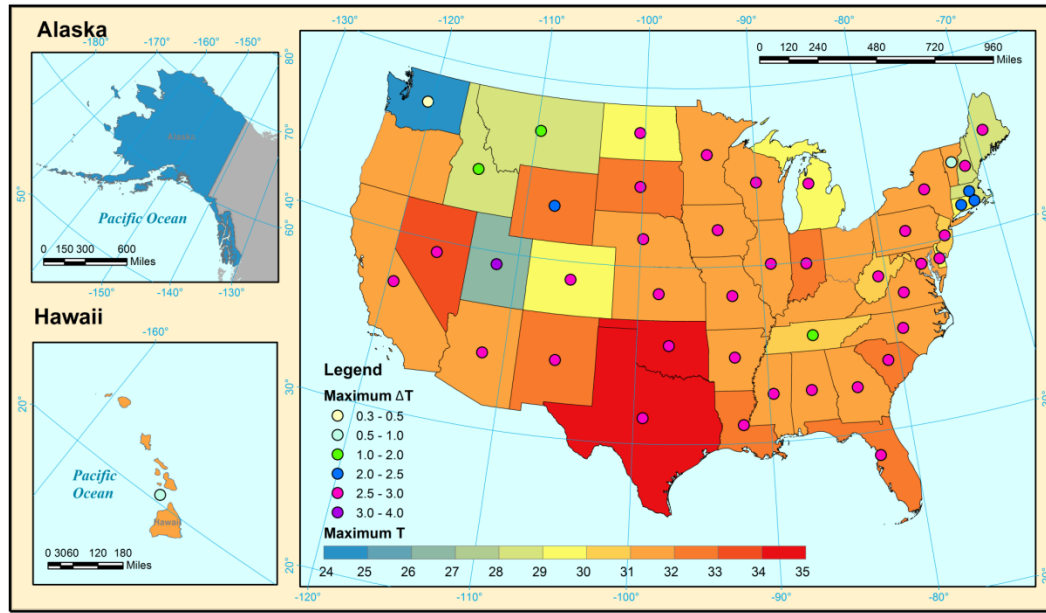
## **2.2 Methodology**

### **2.2.1 U.S. State-level Environmental Regulations**

Current modeling studies display differences in regulatory treatment that encompass three aspects: interpretations of environmental regulation; representations of state/federal standards; and considerations of provisional variance for power plant

operators. In the U.S., the Clean Water Act (CWA) imposes limits on discharges to navigable waters through the National Pollutant Discharge Elimination System (NPDES) Permit Program. CWA section 316(a) established standards on surface water temperature variations due to discharged thermal effluents from industrial sites. Further, the U.S. Environmental Protection Agency (EPA) grants states the authority to administer the NPDES permit program as well as the authority to grant provisional variances for short-term relief from conditions that make permit compliance impossible<sup>38</sup>.

Figure 2-1 displays U.S. state-level water temperature standards including maximum allowable water temperature and temperature rise<sup>39</sup>. More details are found in Appendix A Supplementary Note 1 and Supplementary Table A-2. Southern states generally employ higher thresholds for water temperature and a majority of the states allow a 2.5°C -3°C of temperature rise in freshwater due to thermal discharge from power plants<sup>39</sup>.



*Figure 2-1 EPA state water temperature standards criteria. The scale bar shows maximum allowable water temperature and the colored dots indicate water temperature rise both in units of °C. There are no explicit standards on temperature rise for Alaska, Kentucky, Maryland, Ohio and Oregon.*

## 2.2.2 Modeling Framework

We linked a state-of-the-art regional Earth System Model with a thermoelectric power generation model. The land component of the Community Earth System Model (CESM) is the Community Land Model (CLM) with a large-scale river routing module called the MOdel for Scale Adaptive River Transport (MOSART). Detailed descriptions of the modeling framework and individual components are included in Appendix A Supplementary Methods. CLM-MOSART outputs include daily-averaged natural streamflow and water temperature, which are then used as inputs to the thermoelectric power generation model. Other inputs to the



thermoelectric power generation model include power plant specific technological details with quality control process (Appendix A Supplementary Methods), environmental regulations related to thermal discharges (Appendix A Supplementary Note 1), and climate forcing data from the North American Land Data Assimilation System stage II (NLDAS2). Results were aggregated from daily to monthly scale to be comparable with available historical records.

The coupled hydrological thermoelectric generation model runs at a daily time step for the historical period of 2010 to 2012 driven by climate forcing data from NLDAS2 as well as for the future period of 2013 to 2100 under RCP4.5 and RCP8.5 driven by climate forcing data simulated by the Weather Research and Forecasting (WRF) model at a 20km grid resolution<sup>40</sup>. Only three years of the historical records (2010-2012) were used here since only three years of overlap exist between EIA-923 monthly data and CLM-MOSART historical simulation. EIA-923 data prior to 2010 were recorded at annual time step.

### 2.2.3 Scenario Configurations

We quantify the impact of future climate change in the context of current environmental regulations and compliance contingencies. Two compliance contingencies are examined in which a) power plants shut down if either the ambient water temperature violates CWA limits or the natural streamflow fails to meet environmental flow requirements (no waivers) (Appendix A Supplementary Table A-1), and b) power plants receive waivers to continue operation regardless of extreme environmental conditions (waivers granted). Compliance contingencies will affect power plant usable capacity, which is the maximum electric output an electricity

generator can produce under specific conditions. To avoid power plant de-rating and reduced usable capacity, waivers are granted upon request to provide short-term relief from conditions that make compliance difficult or impossible. A process for waiver approval requires public notice, a description of the methodology, studies, and data documenting the alternative thermal effluent limit will not be detrimental to local aquatic environment<sup>41</sup>. We investigated the implications of provisional variances for three different periods in the future: 2030s (2020-2039), 2060s (2050-2069), and 2090s (2080-2099), representing early, mid and late 21<sup>st</sup> century, under two representative concentration pathways (RCPs) – RCP4.5 and RCP8.5. The RCPs describe a possible range of radiative forcing values by the year 2100 relative to pre-industrial values, which are consistent with a wide range of possible changes in global temperature increase. The RCP4.5<sup>42</sup> and RCP8.5<sup>43</sup> scenarios project moderate (2.4°C) and high (4.9°C) increase in global temperature, respectively.

Note that both past and future time periods account for only the selected power plants that have cooling water requirement (selected samples represent ~44% of existing capacity, see Appendix A Supplementary Methods).

#### 2.2.4 Power Plant Cooling Technologies

Results are represented in this paper for both once-through and recirculating systems. Once-through systems take water from rivers, lakes, or the oceans, circulate it through pipes to remove heat from the condensers, and discharge the water back to its original source at a warmer temperature. Recirculating systems reuse cooling water multiple times before discharging it back to the original water source. Because of the differences in cooling process, once-through systems typically have

significantly higher water withdrawals and thermal pollutions than recirculating systems. Performance of power plant with either cooling system is subject to water level and water temperature variation.

#### 2.2.5 Limitations

In this study, similar to the work of van Vliet et al.<sup>20,25</sup> and Bartos and Chester<sup>23</sup>, we did not link our thermoelectric power plants to the electricity grid system, which will re-optimize power plants to work around local binding constraints. Further, we did not account for climate change impacts on electricity demand, meaning that more electricity will be needed during summer that is likely to become hotter with climate change. This will likely exacerbate the tradeoff between meeting the increasing demand and fulfilling the environmental requirements. Lastly, we focused the assessment on existing power plants, not taking into account of future energy infrastructure, which is outside the scope of this current study. More limitations and implications of this study are included in Appendix A Supplementary Note 3.

### 2.3 Results and Discussions

Historical simulations show that capacity reduction generally occurs during the summer months when electricity demands are greatest (Appendix A Supplementary Figure A-4). This is due to the combined effects of lower summer river flows and higher water temperatures.

Figure 2-2 highlights a seasonal pattern in usable capacity with gradually decreasing usable capacity over time between May and October, especially for once-

through systems (see Methods for cooling technology classification). Compared to the historical record, if no waivers are granted, approximately 8%-14% and 8%-10% of usable capacity will be unavailable for once-through and recirculating systems, respectively, for the months May-October. Granting waivers helps retain most of the usable capacity during the peak demand season (waivers granted); i.e., only 0.1%-3% and 1.8%-2.3% of the usable capacity will be unavailable for once-through and recirculating systems, respectively.

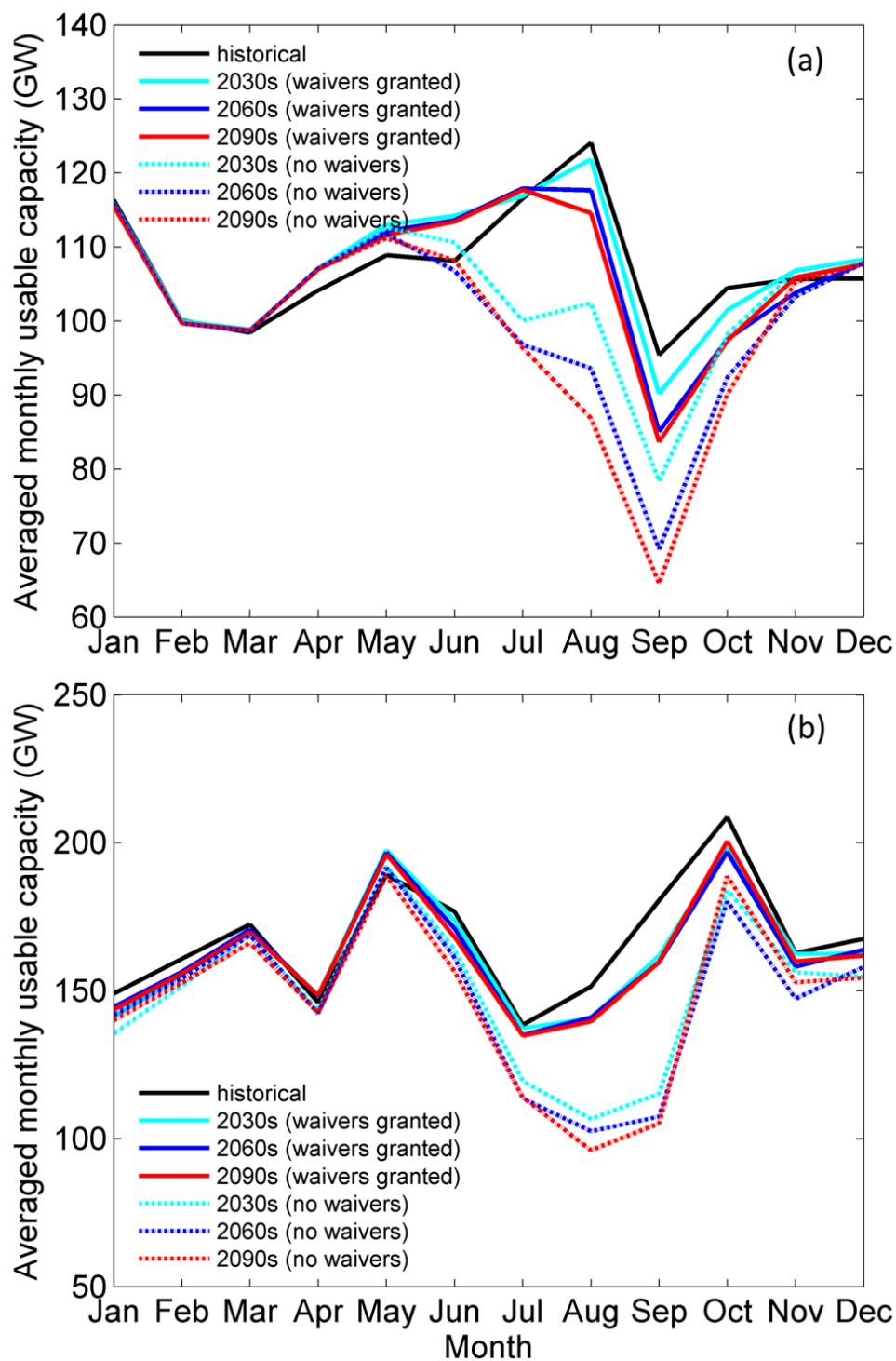
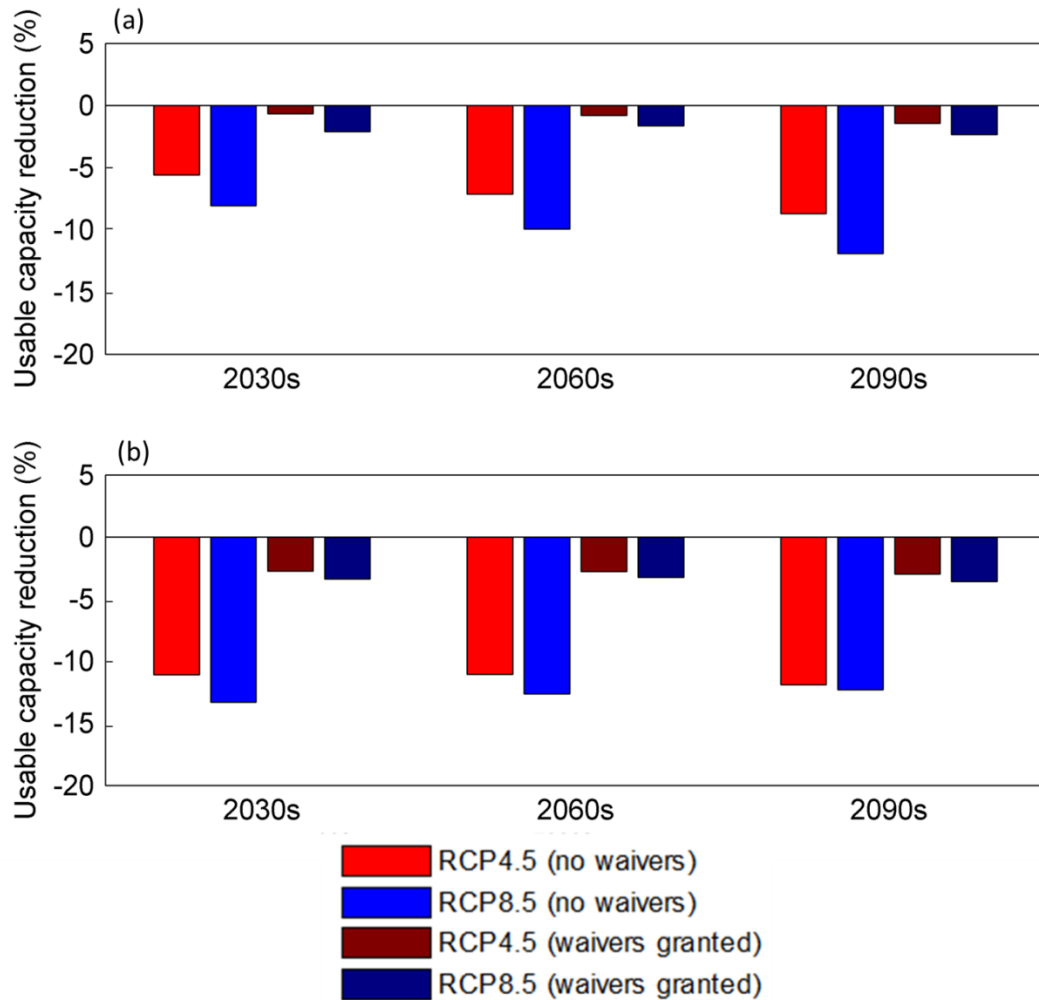


Figure 2-2 Projected average monthly usable capacity under RCP4.5 scenario. Panel (a) is for once-through systems and panel (b) is for recirculating systems. The black line is historical simulation, and the color lines are future projections for the 2030s,

*2060s, and 2090s under two compliance contingencies with the solid line being the waivers granted case and the dotted line being the no waivers case.*

Looking across different time periods in Figure 2-2, total usable capacity for once-through systems is 6%-12% lower relative to historical conditions if waivers are not granted. If waivers are granted, a 1%-2% reduction (relative to historical conditions) is still anticipated due to existing climate variability (Figure 2-3a). Similar results are also observed for recirculating power plants with 11%-14% for the without waivers case and 3%-4% for when waivers are allowed (Figure 2-3b). Recirculating systems appear to be more sensitive to streamflow variability than once-through systems for two reasons. First, recirculating systems often reside in more water-scare regions than once-through systems<sup>44</sup>, and as such are more sensitive to changes in the hydrologic regime. Second, there is no distinction between cooling pond and cooling tower in the EIA inventory; hence, power plants equipped with cooling ponds are less vulnerable to low streamflow conditions because cooling ponds help mitigate low flow conditions. We implicitly considered all recirculating cooling used as cooling tower water, and therefore, our estimate is conservative with regard to the climate change impact on recirculating power plants. Total usable capacity decreases with time regardless of scenarios and technology due to insufficient streamflow. Overall, usable capacity loss is generally greater under RCP8.5 than RCP4.5, suggesting climate change mitigation policy will help to retain 0.6%-3% more usable capacity. This alleviation due to mitigation is more evident for once-through systems because mitigation policies will largely hinder the acceleration of temperature such that CWA

constraints are less frequently encountered (Appendix A Supplementary Figure A-6a).



*Figure 2-3 Average usable capacity reductions under RCP4.5 and RCP8.5 scenarios. Panel (a) is for once-through systems and panel (b) is for recirculating systems. The red bars are RCP4.5 results and the blue bars are RCP8.5 results. Darker colors indicate the waiver granted case and brighter colors indicate the no waivers case.*

## 2.4 Further Discussions and Conclusions

Our estimates of usable capacity loss are less pronounced than other studies that employ different hydrological and thermoelectric generation models. Table 2-1

shows the comparison of projected mid-century usable capacity reduction under the different climate scenarios between this study and the studies of Bartos and Chester<sup>23</sup> and van Vliet et al.<sup>25</sup>. Differences in model configuration between this study and the other two studies are compared in Appendix A Supplementary Table A-4. When waivers are not granted, estimates from this current study fall within the range of published values. However, when waivers are granted, this current study suggests that climate change alone actually has a relatively small direct impact to power generation, which agrees with conclusions drawn from studies based on historical data. Bartos and Chester<sup>23</sup> and van Vliet et al.<sup>25</sup> did not account for the provisional variances, and hence, presumably overestimated the usable capacity reduction due to climate change.

Table 2-1 Estimates of total usable capacity reduction by mid-century

Scenario	Period of study	Percentage change	Reference
A1B	2040-2060	7.4%-9.5%	Bartos and Chester (2015) (Western U.S.)
A2			
B1			
RCP2.6	2050s	7%-12%	van Vliet et al. (2016) (North America)
RCP8.5			
RCP4.5	2060s	2.2% (waivers granted)	This study (entire U.S.)
		10% (no waivers)	
RCP8.5		2.8% (waivers granted)	
		12% (no waivers)	

Power plants currently risk shutdowns due to changes in climate and water availability. Note that currently more than half of all evaporative cooling systems in the U.S. report maximum temperature discharges that exceed the regulated threshold temperature<sup>21,26</sup>. In the past, provisional variances (waivers granted) have been



approved to power plant operators in response to unanticipated environmental factors that make compliance difficult<sup>1</sup>, but waivers are not issued every time in a prompt manner. Therefore, the true effect of climate change on thermoelectric power generation would fall between the waivers granted case and no waivers granted case. In our study, we find that for once-through systems, streamflow constraints account for 32% - 44% of usable capacity reduction while the rest is due to CWA constraints (Appendix A Supplementary Figure A-7). If CWA constraints were to be relaxed, some portions of the usable capacity would be retained to meet electricity demand, but the risks of deteriorating biodiversity which has cascading long-term effects on human society still exist. In the event of droughts and heatwaves, whether to shut down a power plant or to keep the plant running at the expense of uncertain short-term and long-term consequences on aquatic environments is an important tradeoff. A balanced solution to this dilemma is urgently needed given that the need for waivers will continue to rise due to rising temperature and intensifying droughts. For example, in the state of Illinois, requests for waivers have been rarely denied and often processed within one to five days, making provisional variance a remediation for more than short term non-compliance to thermal limits<sup>41</sup>.

For our selected sample of power plants, 2%-3% of the usable capacity will be unavailable by the 2060s due to the effects of climate change. Another 10%-12% of the usable capacity will be unavailable if current environmental requirements are enforced without thermal variance waivers. Our study implies that climate change itself is estimated to have less of an impact on thermoelectric power plants when compared to impacts presented in existing studies. Climate change mitigation policies

will likely alleviate some of these adverse impacts<sup>45</sup>. Further, a majority of the power plants examined in this study are likely to be retired by the 2060s as the current U.S. energy system is gradually transitioned from a fossil fuel-dominated structure to more of a mixture of renewable and non-renewable energy sources. Therefore, on one hand, the U.S. energy system may be more resilient to climate change in the future than implied by this study. On the other hand, growing demands for electricity and water resources are likely to alter the resilience of the U.S. power system from its current state. The findings from our study provide valuable insights to planned capacity additions. For example, the thermoelectric power supply sector does not typically take climate change into account during capacity expansion planning, which may result in overly optimistic forecasts of electricity supply thereby exacerbating future requests for provisional variances<sup>23</sup>. Our study shows that impact of climate change on the U.S. thermoelectric power system is less than previous estimates due to inclusions of state-level environmental regulations, without which less usable capacity would be available; hence, properly accounting for the effects of climate change as well as legal constructs is crucial for the future reliability of the U.S. power supply.

## Chapter 3 Implications of water constraints on electricity capacity expansion in the United States

*This chapter is under review by Nature Sustainability. Full citation is as below:*

*Liu L., M. Hejazi, G. Iyer, and B. Forman (2017), Implications of water constraints on electricity capacity expansion in the United States, Nature Sustainability (under review)*

### 3.1 Introduction

#### 3.1.1 Rationale

Constraints on the availability of water are becoming increasingly important in the U.S. For example, California prohibited the use of freshwater for new thermoelectric development ([California Water Code, 13550-13552](#)) as well as for power plant cooling in desert regions.<sup>46</sup> In particular, water use restrictions during dry seasons are becoming increasingly common. For instance, in 2015, the governor of California issued an executive order for a statewide mandatory water reduction to make California drought resistant<sup>47</sup>. Similar restrictions are also seen in Austin, TX, where permanent water restrictions have been implemented<sup>48</sup>.

Such constraints on the availability of water (henceforth referred to as water constraints) are expected to have important implications on the development of new electricity generation capacity. For instance, among other factors, the California water restriction policy resulted in rapid reduction in the deployment of coal-fired technologies and increased deployment of non-water intensive renewable energies for electricity generation in California<sup>46</sup>. Likewise, concerns about the potential impacts

to local water resources<sup>49</sup> prompted decision makers in Idaho to pass a House bill to place moratorium on coal-fired power plants in the state. Since then, there are no coal-fired technologies in Idaho's electricity portfolio, nor is it expected to resurrect in the future. Concerns about water availability could affect decisions regarding the siting of new power plants as well as the types of technologies to deploy<sup>27,50,51</sup> which could further influence the ability of existing plants to meet the growing electricity demand<sup>52-55</sup>. Accounting for water availability in electricity capacity planning is therefore critical to ensure that strategic resource planning can be accomplished while minimizing economic losses.

### 3.1.2 Objectives and Literature Review

We explore the implications of constraints on water availability for electricity capacity expansion in the U.S. by incorporating physical water constraints in a state-level model of the U.S. energy system embedded within the global change assessment model (GCAM-USA)<sup>56,57</sup>. Previous studies have attempted to incorporate constraints on water availability in electricity capacity expansion, but the resulting impacts vary by study<sup>27-29</sup> (Appendix B Supplementary Table B-1). Webster et al.<sup>29</sup> analyzed water constraints in Texas and demonstrated that under the constraint of meeting a 75% reduction in CO<sub>2</sub> emissions and a 50% reduction in water withdrawals, substantial changes in capital stock may occur in which wet-cooling nuclear and conventional coal capacities will be replaced by wind and natural gas using combined cycle and combustion turbine technology. Macknick et al.<sup>27</sup> focused on the entire U.S. and showed that current water policy and prices have little impact on the national trend by the electricity sector to move towards more utilization of natural gas and renewable

technologies while simultaneously retiring coal-fired and nuclear power plants. Tidwell et al.<sup>28</sup> assessed new electricity generation placements for the western U.S., taking into account water availability constraints, and concluded that construction of low to zero water use generation is favored due to planning constraints but not water constraints. Our study extends these analyses in two important ways. First, our modeling includes interactions of the electricity sector with other sectors of the economy. In particular, GCAM-USA tracks electricity demand and supply for the U.S. at the state-level along with electricity trade across states. Second, our state-level model allows us to demonstrate the heterogeneity in the impacts of water constraints and potential challenges across states (Appendix B Supplementary Note 1).

Our results suggest that water availability constraints may cause substantial capital stock turnover and result in non-negligible economic costs for the western U.S. while fewer impacts may be anticipated in the eastern U.S. Water constraints might also impose increased stress on existing electricity transmission lines as some states become more reliant on imported electricity from other states that have more flexibility to adapt to water constraints. Our results suggest the need to integrate water availability constraints into electricity capacity planning so as to better understand state-level challenges, facilitate strategic resource planning, and minimize economic losses.

## **3.2 Methodology**

### **3.2.1 Water Withdrawal for Electricity Generation**

Water withdrawal for the electricity sector is modeled in GCAM-USA by assigning a water withdrawal coefficient ( $\text{km}^3/\text{MWh}$ )<sup>58</sup> to each technology

represented at the level of state, including primary fuel, generation type, and cooling technology. In this study, cooling technology shares prior to year 2010 are based on the UCS EW3 Energy-Water Database V.1.3 (<http://www.ucsusa.org/clean-energy/energy-water-use/ucs-power-plant-database#.WanL38iGOUk>). Beyond year 2010, we adopted the approach in Liu et al.<sup>44</sup> for cooling share assumptions of frozen scenario in which future cooling share stays the same as in the historical year of 2008.

### 3.2.2 GCAM-USA

The Global Change Assessment Model (GCAM) is a global integrated assessment model developed and maintained at the Pacific Northwest National Laboratory, designed for long-term analysis of energy supply and demand, agriculture and land use, greenhouse gas emissions, and climate. GCAM is also a community model which can be obtained at <http://www.globalchange.umd.edu/gcam/download/>. For the purposes of the present study, only the components of the model relevant for the assessment of the electric sector water demand are described. The full description of GCAM can be found on the GCAM Wiki (<http://jgcri.github.io/gcam-doc/>) and in a series of publications<sup>59–62</sup>. GCAM-USA builds on GCAM by extending the framework to model electricity markets at the U.S. state level instead of the original, national level. There are nine fuel types, or sources of energy, for electricity generation in GCAM-USA: coal, gas, oil, biomass, nuclear, geothermal, hydro, wind, and solar. They can be used to produce power using a wider range of production technology options that are also tracked in GCAM-USA. Future regional electricity demand is driven by growth in demand for energy services by the buildings, industrial, and transportation sectors, which in turn are driven by exogenous

assumptions about population and income in each region that are modified by technological aspects of energy service provision <sup>8</sup>. GCAM-USA calculates the annual electricity generation by fuel type and generation technology in each of the 50 states at 5-year intervals from 2005 to 2100, and includes power plant retirements and new additions. The new power production capacity mix depends at least, in part, on expected production costs for each fuel-technology option. Capital stocks are modeled explicitly. As a result, the generation mix of new builds in any time period depends largely on the characteristics of available technologies and on energy prices in that time period, but the total generation mix also incorporates the decisions made in prior time periods.

### 3.2.3 Water Constraint Scenarios

Available water supply for the electricity sector was treated as a constraint such that additions of new electricity capacity would have to adapt to water sufficiency and economic viability. We represent water constraints by considering current water allocation practices in the U.S. (Appendix B Supplementary Note 1) and by assuming only a fraction of the available water resources is appropriated to the electricity sector<sup>2</sup>. Available water supply for the electricity sector includes two parts: water withdrawal for electricity generation and untapped water available for the electricity sector. Data sources and computation of available water supply are included in Methods.

Available water supply for the electricity sector was computed as the summation of electricity water withdrawal in year 2010 (GCAM-USA last calibration year) and untapped water available for the electricity sector as:

$$Q_{A,i} = Q_{2010W,i} + \alpha_i Q_{U,i} \quad (3.1)$$

$Q_{A,i}$  is available water supply for the electricity sector for state  $i$ .  $Q_{2010W,i}$  is state-level electricity water withdrawal in 2010, which is a model output from GCAM-USA.  $\alpha_i$  is the fraction of water withdrawal allocated to the electricity sector in year 2010 and this is determined by the U.S. Geological Survey (USGS)<sup>2</sup>. Untapped water availability data,  $Q_{U,i}$ , was obtained for the western states from Tidwell et al.<sup>63</sup> and for the eastern states from Tidwell et al.<sup>64</sup>. The complete list of values is provided in Supplementary Table B-2.

We configured three water constraints scenarios to investigate the impact of increasing stringency. Scenarios include: 1) *no water constraint*; 2) *current water availability* and 3) *severe water constraint* (50% of current water availability). Severe water constraint is selected to describe a water-scarce world and it is meant to be a proof-of-concept scenario. If the available water supply falls below the estimated withdrawal demand based on the no water constraint scenario, then water availability has a binding effect on electricity capacity expansion. Otherwise, water availability is considered non-binding to electricity capacity planning (Appendix B Supplementary Figure B-1).

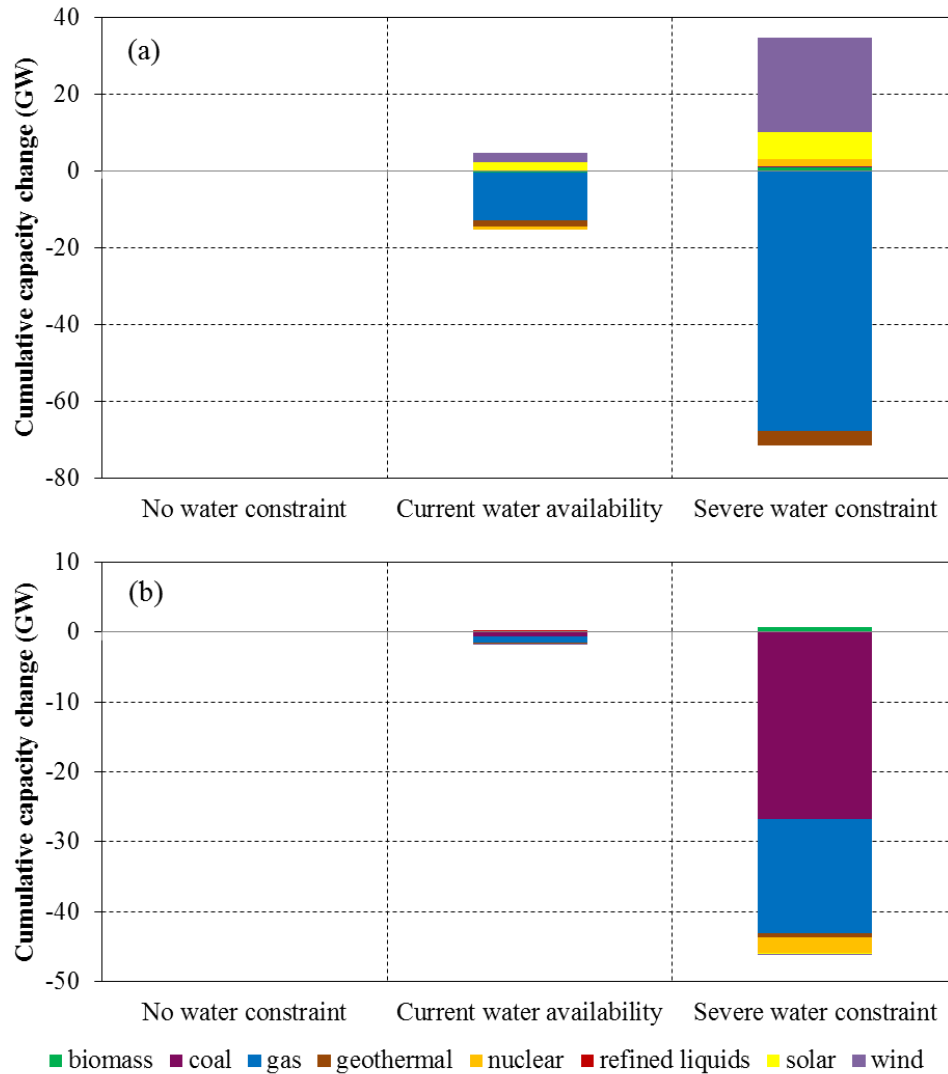
### 3.3 Results

#### 3.3.1 Effects of Water Constraints on Electricity Capacity Expansion

In general, limiting water supply to the electricity sector increases electricity prices. This leads to an overall reduction in electrification of end-use sectors (Appendix B Supplementary Figure B-2), and therefore, less total electricity



generation (Appendix B Supplementary Figure B-3). Investment in new capacities and treatment of existing capacities could also be altered when water availability becomes a binding factor. Figure shows the impact of increasing water constraints on electricity capacity expansion. As water constraints become more stringent, it is more economically viable to invest in less water-dependent technologies such as wind and solar photovoltaic (Figure 3-1a) rather than in gas-fired technologies which are water-intensive. Furthermore, increasing water constraints also leads to more forced retirements of water-intensive fossil fuel based technologies such as thermoelectric coal and gas, often before the end of their designed lifetimes (Figure 3-1b). It is difficult to monetize forced-retired capacities as their future monetary values are uncertain, however, such loss could be minimized by more informed capacity planning with consideration of water constraints. The loss of existing capacities is compensated by new additions in wind and solar photovoltaic technologies. Cumulative capital investment in new capacity additions over the period of 2011-2050 is estimated at ~\$1.1 trillion dollars when water availability is unlimited. Under the severe water constraint scenario (i.e., 50% of current water availability), cumulative investments drop by ~1.6% with ~\$40 billion dollars in increased investment in wind and solar photovoltaic and ~\$55 billion dollars in divestment of gas-fired technologies (Appendix B Supplementary Figure B-4).



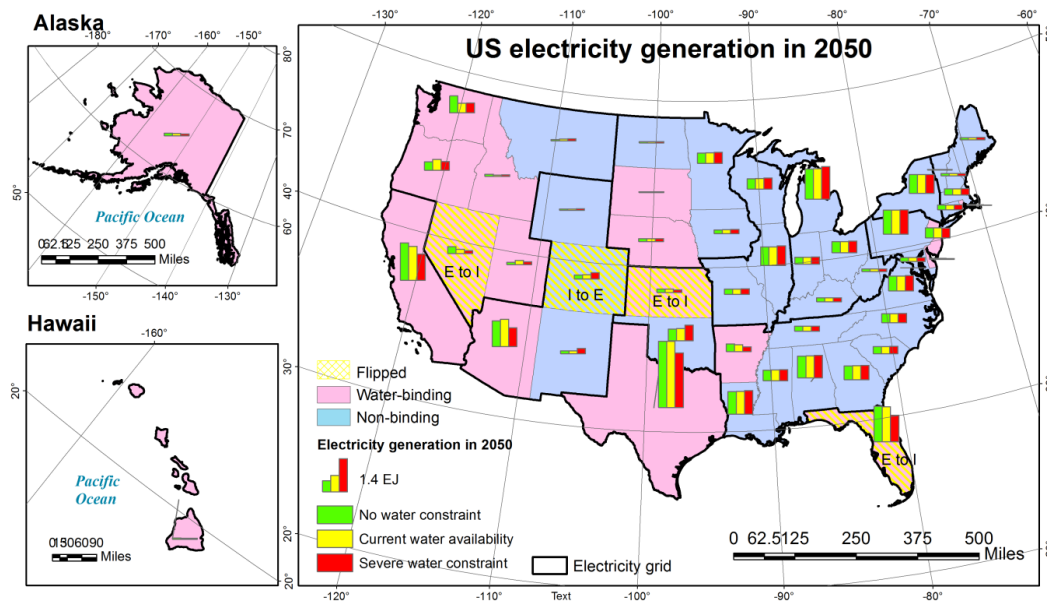
*Figure 3-1 Cumulative capacity change (2011-2050) by fuel relative to the no water constraint scenario for (a) additions and (b) forced retirements.*

### 3.3.2 Regional Dynamics and Challenges

Overall, the introduction of water availability constraints results in reduced electrification of end-use sectors due to higher electricity prices (Appendix B Supplementary Figure B-3). However, this effect is heterogeneous across the U.S. as the degree of impact varies from state to state. Figure 3-2 shows electricity generation

in 2050 under the no water constraint, current water availability, and severe water constraint. There is discernible longitudinal gradient from West to East - the impacts of water constraints on electricity capacity expansion are more pronounced in the West than in the East.

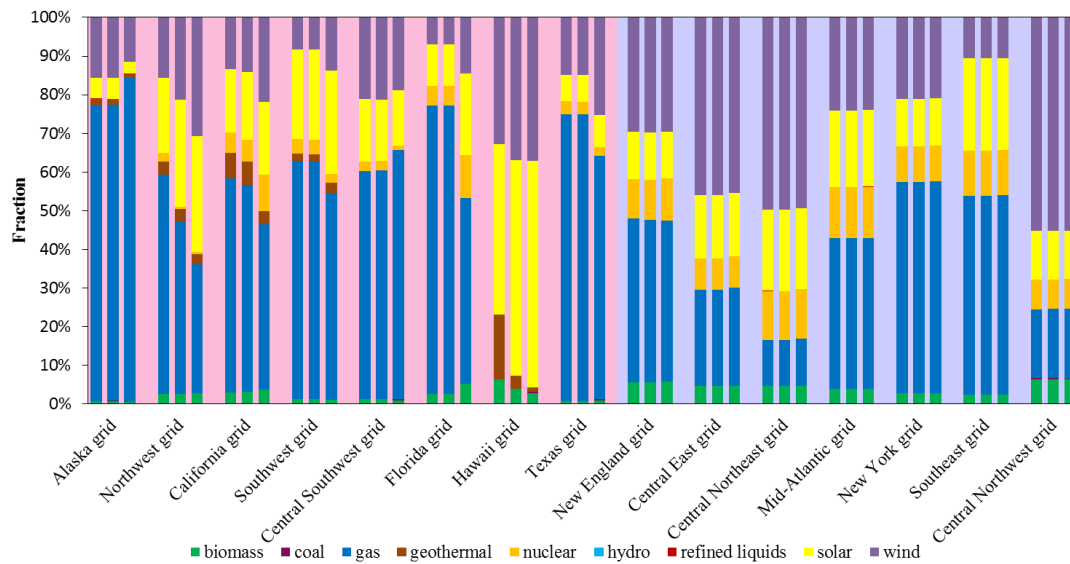
In general, water constraints result in reduced electrification of end-use sectors for water-binding states and exert very little or even positive impact for non-binding states. The constraints as designed in our experiments are non-binding in a number of states in the West. Such states end up producing more electricity under severe water constraints in order to partially account for the reduced electricity generation in neighboring, water-binding western states. For example, Nevada and Kansas switch from being net exporters of electricity to net importers whereas Colorado switches from being a net importer to a net exporter, all of which are the result of cost-effective considerations. On the other hand, the eastern states experience much less significant impacts because the constraints are non-binding (by design), except for Florida. Florida is unique in that the state switches from being a net exporter of electricity to being a net importer in order to accommodate for within-state electricity demand.



*Figure 3-2 Electricity generation in 2050 under three water constraint scenarios: no water constraint, current water availability and severe water constraint. Pink color indicates that water is binding in 2050 and blue indicates otherwise; yellow shaded states flip their traditional trading regime under the severe water constraint scenario); thick black boundary lines represent the fifteen North American Electricity Reliability (NERC) regions.*

In addition to reduced total electricity generation in the West due to water constraints, there is also change in future investment patterns, which is most apparent in the western grid regions and Florida (Figure 3-3). Electricity grid regions in this study refer to groups of states that are defined to closely match the North American Electricity Reliability (NERC) regions (Appendix B Supplementary Figure B-5). As water availability becomes severely limited, the western grid regions adapt to the water constraint by relying more on wind and solar photovoltaic technologies to meet demand. Investment in gas-fired technologies that are more water intensive relative to

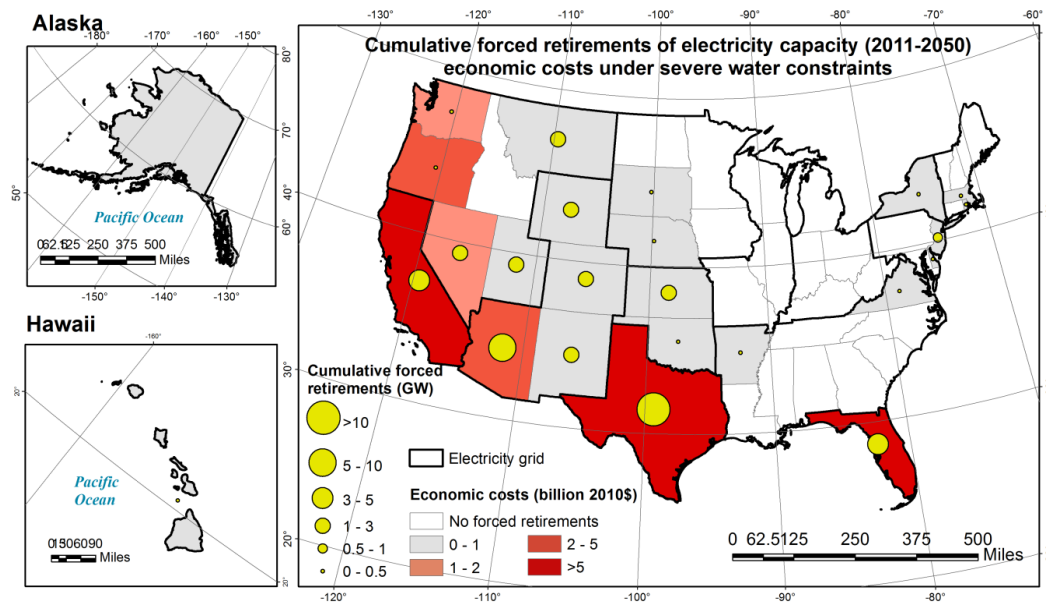
wind and solar technologies becomes less economically viable, and therefore, more expensive to operate when water is treated as a binding factor. It is also important to note that the eastern grid regions are much less impacted by the existence of water constraints as investment behaviors in new electricity capacities remain unchanged.



*Figure 3-3 Fractions of cumulative capacity additions (2011-2050) by fuel for each electricity grid region. The first bar is no water constraint scenario, the second bar is current availability scenario and the third bar is severe water constraint scenario. Pink regions indicate water-binding effect and blue regions indicate no water-binding effect.*

Forced retirements mostly occur in the western grid regions (Figure 3-4) with Texas, Arizona, California, and Florida accounting for ~70% of the total forced-retired capacities by 2050 (Appendix B Supplementary Figure B-6). As water supply becomes increasingly scarce, the implied cost of achieving the water constraint while meeting the electricity demand increases, resulting in an increase in forced retirement of existing, water-intensive generation capacities, particularly in the western grid

regions (Figure 3-4). The magnitude of the cost indicates the degree of difficulty embodied in the response of the electricity system to adapt to the water constraint. Under the severe water constraint scenario, the total cost for the U.S. in 2050 is ~0.17% of GDP, which could be reduced or minimized with adaptation strategies including but not limited to energy transformations towards less water-intensive technologies at early stage.



*Figure 3-4 Cumulative forced retirements of electricity capacity from 2011 to 2050 and the economic costs of achieving the severe water constraint (billion 2010\$). The cost of achieving the severe water constraint is computed as the integrated area under the marginal cost curve of meeting the water constraint.*

Apart from changing investment patterns and inducing economic costs, water availability constraints may also modify dynamics of regional electricity trade. In general, states with weakly binding constraints export a larger fraction of the in-state generated electricity to states where constraints are strongly binding (Figure 3-5). This puts net importer states in higher reliance on net exporter states, which further

stresses the existing electricity transmission system. Exceptions to the general pattern include West Virginia where water is non-binding yet the state imports more electricity. For West Virginia, ~94% of the net electricity generation comes from coal-fired power plants<sup>65</sup>. Although water availability is not a limiting factor for future capacity expansion in West Virginia, it becomes more economically viable to import electricity from neighboring states than to produce electricity domestically using coal-based technologies, especially when coal-fired power plants without carbon capture and sequestration (CCS) do not meet electric power sector policies on new generation units<sup>66</sup>. Alternatively, Oregon and Nebraska display the opposite pattern in which water is binding yet both states export more electricity. Oregon depends heavily on hydroelectric generation for meeting its electricity demand<sup>65</sup>. Therefore, the deployment of hydropower in the model is set exogenously<sup>56</sup>, hence, water constraints would have little impact on hydroelectric production. In the case of Nebraska, wind resources are abundant<sup>65</sup>, therefore, it is economically viable for Nebraska to produce electricity from wind technologies that are not water dependent, and export electricity to neighboring states that have less flexibility to adapt to the water constraints. Four states that display flipped trading regime further suggest the urgent need to incorporate water constraints into capacity planning as there are vital economic and social implications.

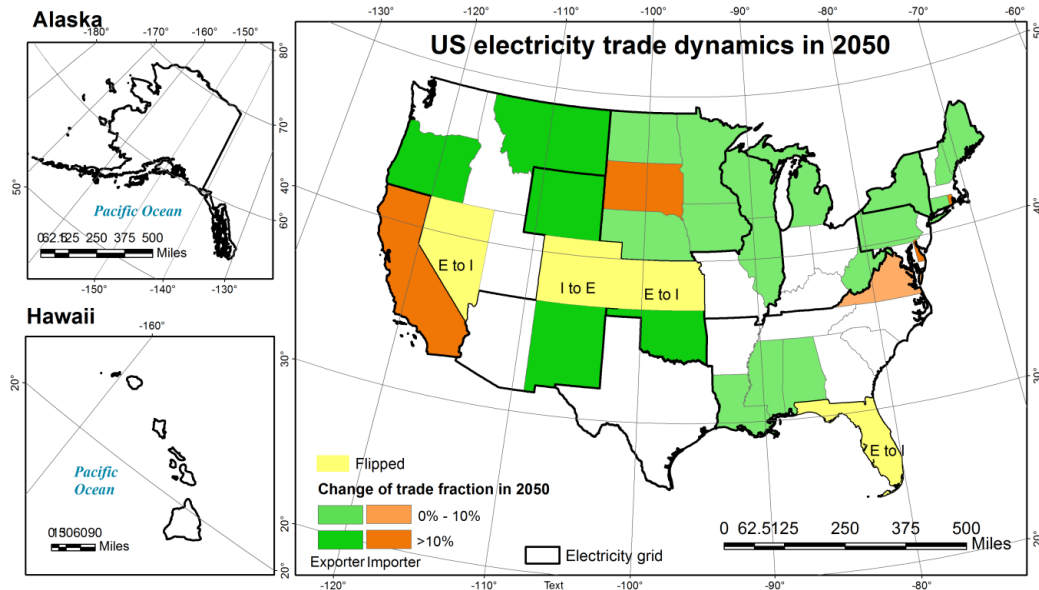


Figure 3-5 Change in US electricity trade fraction by 2050 under the severe water constraint scenario as compared to no water-binding constraints. Trade fraction is the fraction of electricity generated within state being exported (for net exporters) or the fraction of electricity consumed within state being imported (for net importers) (Appendix B Supplementary Note 2). Green and orange colors indicate intensified electricity trade whereas yellow indicates a complete flip in trading regime. “E” means net exporter. “I” means net importer.

### 3.4 Future Work and Final Remarks

This study is not without limitations. We have explored only one adaptation strategy in response to water constraints, namely a shift toward less water intensive technologies. Other strategies could potentially include a shift in the cooling technologies. It is estimated that switching to recirculating cooling technology from the more traditional, once-through cooling technology can reduce water withdrawal 10 to 100 times per unit of electricity generated<sup>58</sup>. Utilizing dry cooling or using non-



freshwater sources for cooling could also significantly reduce the dependency on freshwater resources. However, these alternatives are sometimes limited by local readily available resources and may result in increased water loss through evaporation in the case of recirculating technology<sup>44,67</sup>, which could lead to cost and performance penalties<sup>27</sup>. In this study, we exogenously assumed cooling technology shares for the future period based on best judgment. Another adaptation alternative is to add new transmission lines or enhance existing transmission infrastructure. However, new challenges may exist in terms of planning and permitting requirements. In our model, we assume that long-distance transmission capacity does not expand beyond current levels. This assumption is important and requires further research.

Nevertheless, we explore the implications of water availability constraints in the U.S. to electricity capacity planning and find that there are common and diverse challenges across the states. We demonstrate that when water becomes a binding factor, electricity capacity expansion might be vastly different in comparison with a scenario without any water constraints. For example, under water constraints, it might be viable to retire coal- and gas-fired power plants in certain regions, and in turn import from regions where it is economically viable to invest in wind and solar technologies. Our study also suggests that the impact of water constraints on capital stock turnover would be more pronounced in the western states in the absence of cooling technology transformations. In addition, existing transmission lines could be further stressed as some states become more reliant on imported electricity with water constraints. Finally, our study also shows that the economic costs associated with the water constraints could be non-negligible and adaptation strategies are needed to

minimize such cost. All in all, this study suggests that water resource considerations should be factored into electricity capacity expansion planning to facilitate transformation of the energy system and minimize economic losses.

## Chapter 4 Quantifying impacts of climate change and competing land-use on the potential for reservoirs to secure surface water yields in the world's largest river basins

*This chapter was under review by Environmental Research Letters. Full citation is as below:*

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### **4.1 Introduction**

#### 4.1.1 Rationale

Surface water reservoirs help damp flow variability in rivers while playing a critical role in flood mitigation, securing water supplies, and ensuring reliable hydropower generation. In 2011, global reservoir storage was approximately 6197 km<sup>3</sup> and affected the flow in almost half of all major river systems worldwide<sup>68</sup>. Changes in natural flow patterns can disrupt local ecosystems<sup>69,70</sup>, and inundation of upstream areas during reservoir development can cause conflicts with existing land uses<sup>71</sup>. Reservoirs also require a significant amount of resources to plan, build and operate, with implications for long-term water supply costs and affordability<sup>72</sup>. Quantifying exploitable reservoir capacity is therefore crucial for strategic planning of water, energy and food supplies in the coming decades, particularly with

anticipated population growth and exacerbating impacts on hydrological variability due to climate change<sup>5,73–76</sup>.

#### 4.1.2 Literature Review

Storage-yield (S-Y) analysis is often used by water resource planners to determine the reservoir storage capacity required to provide firm yield<sup>77,78</sup>. The firm yield represents the maximum volume of water that can be supplied from the reservoir for human purposes (e.g., irrigation, municipal supply, etc.) under a stated reliability. A number of previous studies propose different algorithms for modeling the S-Y relationship<sup>79</sup>, and have included storage-dependent losses<sup>80</sup> and generalized functional forms for broader scale application<sup>81–83</sup>. For example, McMahon et al.<sup>31</sup> developed six empirical equations to calculate reservoir capacities for 729 unregulated rivers around the world. A number of other previous studies employ S-Y algorithms to provide insight into various water security challenges moving forward. Wiberg and Strzepek<sup>72</sup> developed S-Y relationships and associated costs for major watershed regions in China accounting for the effects of climate change. Analogously, Boehlert et al.<sup>5</sup> computed S-Y curves for 126 major basins globally under a diverse range of climate models and scenarios to estimate the potential scale of adaptation measures required to maintain surface water supply reliability. Gaupp et al.<sup>30</sup> also calculated S-Y curves for 403 large-scale river basins to examine how existing storage capacity can help manage flow variability and transboundary issues. Basin scale S-Y analysis provides estimates on hypothetical storage capacity required to meet water demand, and hence, such analysis helps to identify the need for further infrastructure investments to cope with water stress on a global scale<sup>30</sup>. Even though

previous analyses of both global and regional energy systems suggest that evaporative losses from reservoirs used for hydropower play a significant role in total consumptive water use<sup>84,85</sup>, such evaporative impacts are missing from existing global-scale assessments of surface water reservoir potential that consider climate change. Increasing air temperatures and variable regional precipitation patterns associated with climate change will ultimately affect evaporation rates. Moreover, competing land uses and environmental flow regulations play an important role in large-scale reservoir siting and operations, but have yet to be considered concurrently as part of a global-scale assessment of the ability of future reservoirs to provide sustainable firm yields under climate change. Additional constraints on reservoir operation and siting will reduce firm yields, but these effects could be offset in basins where runoff is projected to increase under climate warming<sup>86</sup>. Development of new, long-term systems analytical tools to disentangle the tradeoffs between potential reservoir firm yield, climate change, and competing land-use options is therefore a critical issue to address from the perspective of water resources planning.

#### 4.1.3 Objectives

The purpose of this study is to assess the aggregate potential for reservoirs to provide surface water yields in 235 of the world's largest river basins, including consideration of climate change impacts on basin-wide runoff and net surface flux (i.e., the difference between estimated evaporation from the reservoir surface and the incident precipitation), as well as constraints on reservoir development and operation due to competing land uses and environmental flow requirements. Improved basin-scale S-Y analysis tools enabling global investigation are developed for this task,

including a linear programming (LP) framework that contains a reduced-form representation of reservoir evaporation and environmental flow allocation as endogenous decision variables. The framework incorporates additional reservoir development constraints from population growth, human migration, existing cropland, and natural protected areas. We further consider a range of future global change scenarios and measure reservoir performance in terms of yield and corresponding reliability as to maintain a given yield across global change scenarios. The scope of this analysis thus covers a number of important drivers of water supply sustainability neglected in previous global assessments while also providing new insight into the following research questions:

- What are the impacts of competing land-use activities and environmental flow constraints on the potential for expanded reservoir capacity needed to secure freshwater yields?
- Where are policies and infrastructure investments needed to sustain and improve global water security?

## **4.2 Methodology**

This study assesses aggregate reservoir storage potential and surface water firm yields at the basin scale. River basins represent the geographic area covering all land where any runoff generated is directed towards a single outlet (river) to the sea or an inland sink (lake). The approach builds on previous work that combines basin-averaged, monthly runoff data with a simplified reservoir representation to derive the S-Y relationships for different basins in a computationally efficient way<sup>5,30,72</sup>. Wiberg and Strzepek<sup>72</sup> tested a similar basin-scale approach to S-Y analysis using a number

of simplified geometries for cascaded reservoir systems in the Southwest United States and showed relatively good agreement with management strategies simulated with a more complicated model. The resulting S-Y relationships quantify the storage capacity needed to achieve a specified firm yield but do not prescribe locations for reservoirs within each river basin. The S-Y relationships provide a metric for understanding how changes in precipitation, evaporation, and land use across space and time translate into changes in required storage needed at the basin level to ensure a specified volume of freshwater is available for human use (e.g., irrigation, municipal supply, etc.). The basin-level S-Y indicators enable comparison across regions, and hence, identification of basins with the greatest challenges in terms of adapting to future climate change<sup>5,72</sup>.

A linear programming (LP) model computes the S-Y characteristics and is applied to the 235 basins delineated in HydroSHEDS used by the Food and Agriculture Organization of the United Nations (FAO) (<http://www.fao.org/geonetwork/srv/en/metadata.show?id=38047>). The LP model calculates the minimum reservoir capacity required to provide a given yield based on concurrent 30-year average monthly runoff sequences within each basin. This timeframe is selected to mimic existing regional water resource planning practices, which typically takes a multi-decadal perspective to include analysis of long-lived infrastructure investments such as reservoir development<sup>30</sup>.

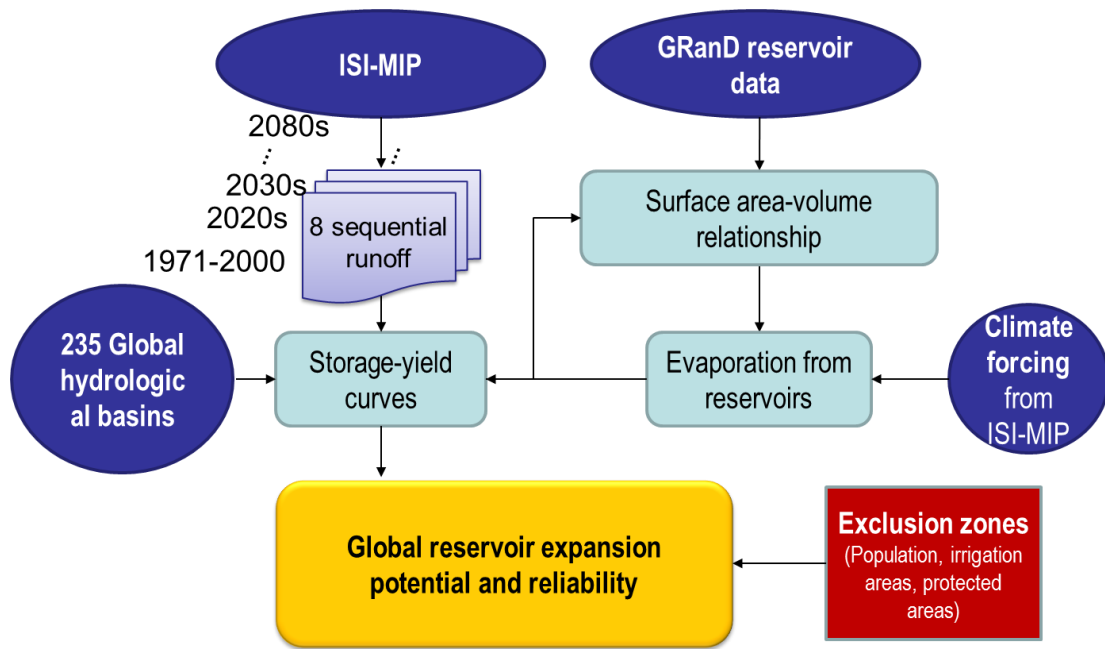
Return of extracted groundwater to rivers and long-distance inter-basin transfers via conveyance infrastructure are important parts of the surface water balance in some regions<sup>87,88</sup>, but are not included in this current study due to lack of

consistent observational data on a global scale and computational challenges preventing application of the LP framework at higher spatial resolutions. The approach also does not consider streamflow routing within basins. The impacts of internal basin routing become less significant at the selected temporal resolution (i.e., monthly)<sup>89</sup>. It is also important to note that in some of the largest basins the hydraulic residence time is on the order of several months, therefore, our analysis is unable to reflect the effects of this time-lag on storage reliability. Analogously, our assessment is unable to address capacity decisions focused on addressing floods, which usually requires assessing flow patterns at higher frequencies<sup>89</sup>.

Implicitly, we assumed that the available land in each basin could be flooded by reservoir development under a maximum reservoir expansion scenario. Available land is defined following a spatially-explicit analysis of existing and future land use in each basin (section 4.2.3). It is important to emphasize that additional reservoir development constraints not readily quantifiable with existing methods (e.g., soil stability, future habitat conservation, cultural preferences, etc.) are likely to further reduce available area for reservoir expansion.

The overall approach of the global scale assessment is shown in Figure 4-1. The historical period of 1971-2000 and a simulation period of 2006-2099 were analyzed for each of the 235 basins. The 30-year monthly runoff sequences were generated for each decade resulting in 8 decadal runoff sequences for each climate scenario. Additionally, the impacts of net evaporative losses from the reservoir surface were estimated for each climate scenario and included in the reservoir capacity calculations.





*Figure 4-1 Framework for assessing impacts of climate change and human development constraints on the reservoir potential in 235 large-scale river basins*

*(GRandD means Global Reservoir and Dam (GRandD) Database).*

#### 4.2.1 Model inputs

For this study, we utilized runoff from a state-of-the-art global hydrological model (GHM) entitled PCR-GLOBWB<sup>90</sup>. Similarly, we used climate inputs from an advanced general circulation model (GCM) entitled HadGEM2-ES<sup>91</sup>, provided by the Inter-Sectoral Impact Model Intercomparison Project (ISI-MIP) Fast Track<sup>92</sup>. PCR-GLOBWB estimates of daily runoff are driven by climate inputs from bias-corrected HadGEM2-ES<sup>92</sup>. The GHM is well-validated over most of the large rivers at both monthly and daily time scales<sup>93,94</sup>. Hydrologic outputs from the GHM driven by a GCM have been applied in global scale studies<sup>95–97</sup>. In this study, the monthly runoff statistics are given based on daily runoff.

Similarly, net evaporative loss from the reservoir is forced by climate input from the GCM using the general approach of Shuttleworth<sup>98</sup> (Appendix C Supplementary Methods 2). This approach originated from the Penman equation<sup>99</sup> and is widely used to estimate the potential evaporation of open water and fully-saturated land surfaces<sup>100</sup>. Net surface flux is therefore the difference between estimated potential evaporation from reservoir surface and precipitation on reservoir surface.

All model inputs are provided as gridded data at 0.5-degree spatial resolution (approximately 50 km by 50 km in the mid-latitudes). Data for each of the four future climate change scenarios from the Representative Concentration Pathways (RCP)<sup>101</sup> are available. The four RCPs (2.6, 4.5, 6.0 and 8.5) describe a possible range of radiative forcing values by the year 2100 relative to pre-industrial values, which are consistent with a wide range of possible changes in global climate patterns. For example, the RCP2.6 scenario represents a low-carbon development pathway consistent with limiting global mean temperature increase to 2 degrees C by 2100<sup>101</sup>. Conversely, RCP8.5 represents a world with high population, energy demand, and fossil intensity, and thus the highest carbon emissions<sup>43</sup>. The inclusion of different global emission scenarios in the S-Y analysis provides insight into the potential interactions with climate change mitigation policy.

Similar to previous research, a simplified geometry for the representative reservoir in each basin is assumed<sup>5,30,72</sup> (Appendix C Supplementary Methods 1). The simplification is crucial in the current study for facilitating the long-term global-scale perspective needed to assess impacts of climate change across multiple scenarios. The

Global Reservoir and Dam (GRanD) database<sup>68</sup> reports the maximum storage capacity and surface area for existing reservoirs with a storage capacity of more than 0.1 km<sup>3</sup>. These data are used to derive an average surface area-volume relationship for each basin (Appendix C Supplementary Methods 1).

#### 4.2.2 Reservoir storage-yield relationship

Reservoir capacity is defined in this study as the minimum storage capacity  $c$  capable of providing a firm yield  $y$  across a set of  $N$  discrete decision-making intervals,  $T = \{t_1, \dots, t_N\}$ . Considering average monthly runoff  $q$ , releases for environmental purposes  $r$  and net evaporative losses  $v$ , a simple water balance across basin-wide inflows and managed outflows at the representative basin reservoir results in the following continuity equation for the storage level:

$$s_{t+1} = s_t + q_t - v_t - r_t - y \quad \forall t \in \{t_1, \dots, t_{N-1}\} \quad (4.1)$$

where  $s$  is the storage level. Evaporation and precipitation are important processes to parameterize in the reservoir water balance due to the feedback with management strategies<sup>72</sup>. Level-dependent net evaporative losses are estimated assuming a linearized relationship between surface area and storage level<sup>80</sup>:

$$v_t = e_t \cdot A_t = \frac{1}{2} \cdot e_t \cdot a \cdot (s_t + s_{t+1}) = \alpha_t \cdot (s_t + s_{t+1}) \quad \forall t \in T \quad (4.2)$$

where  $e$  is the net surface flux (as equivalent depth),  $A$  is the reservoir surface area,  $a$  is the surface area per unit storage volume (Appendix C Supplementary Methods 1), and  $\alpha = 1/2 \cdot e \cdot a$ . The net surface flux and reservoir geometry parameters represent basin averages.

Combining (4.1) and (4.2) generates a continuity equation for the reservoir storage level that incorporates level-dependent net evaporative losses in a simplified way (Appendix C Supplementary Methods 2). The continuity equation is joined with a number of operational constraints to form the following LP model:

$$\text{Min } c \quad (4.3a)$$

$$\text{s.t. } (1 - \alpha_t) \cdot s_t - (1 + \alpha_t) \cdot s_{t+1} - r_t = y - q_t \quad \forall t \in \{t_1, \dots, t_{N-1}\} \quad (4.3b)$$

$$s_{t_1} \leq s_{t_N} \quad (4.3c)$$

$$\rho \cdot c \leq s_t \leq \varphi \cdot c \quad \forall t \in T \quad (4.3d)$$

$$r_{min} \leq r_t \leq r_{max} \quad \forall t \in T \quad (4.3e)$$

$$0 \leq c \leq c_{max} \quad (4.3f)$$

where the management variables are defined by the set  $X = \{s, r, c\}$ . The objective function (4.3a) seeks to minimize the storage capacity given a certain firm yield. Constraint (4.3b) is the continuity equation incorporating level-dependent net evaporative losses. Constraint (4.3c) prevents pre-filling and draining of the reservoir in the model by ensuring the storage level at the final time-step,  $t_N$ , does not exceed the storage level at the initial time step,  $t_1$ . Constraint (4.3d) ensures the reservoir storage level stays within a maximum fraction of storage capacity,  $\varphi$  (assumed to be 1), and a minimum dead-storage limit of the installed capacity,  $\rho$  (assumed to be 0.15 in this study).

Constraint (4.3e) ensures the release is maintained between the maximum and minimum environmental flow requirements,  $r_{min}$  and  $r_{max}$ , which are computed by applying an augmentation factor on monthly natural streamflow. We adopted the environmental flow approach of Richter et al.<sup>69</sup> where the environmental flow

allocation is determined by an allowable augmentation from presumed naturalized conditions. We experimented with an augmentation factor of 10%-90% of the naturalized conditions. Results are shown with an augmentation factor of 90%, which serves as a lower bound for illustrative purposes. As a result,  $r_{min}$  and  $r_{max}$  are 10% and 190% of monthly natural streamflow, respectively. Constraint (4.3f) limits installed storage capacity to  $c_{max}$  and ensures the capacity remains positive. The maximum volume is set based on an assessment of within-basin land use, which is further discussed in section 4.2.3.

Solving (4.3) identifies the minimum storage capacity required to provide the given firm yield subject to the operational constraints. The S-Y relationship is obtained by solving the model for incrementally increasing firm yields. From the S-Y curve, the maximum storage capacity for the reservoir within each basin occurs at the maximum firm yield, i.e., where the marginal gains in yield under reservoir expansion approach zero. Maximum reservoir storage potential is therefore equivalent to the maximum storage capacity derived from the S-Y relationship unless such storage capacity is constrained by available land, which is explained in section 4.2.3. The maximum gain in yield is thus the difference between the current yield and the maximum firm yield identified from the generated S-Y curve.

An ensemble of S-Y curves is generated for each basin using the climate scenarios and multi-decadal simulations described in section 4.2.1. The ensemble is assessed to calculate the number of S-Y curves in each basin that reach a given firm yield. This analysis provides an additional reliability-based performance metric that incorporates a measure of climate change uncertainty. The reliability in this case

represents the probability a certain firm yield can be obtained across the climate scenarios and multi-decadal planning horizons. That is, we assessed reliability in terms of reservoir potential and yields across different climate scenarios and decision-making periods.

#### 4.2.3 Exclusion zones

Reservoir expansion, and the associated gains in firm yield, are constrained by the availability of land since not all areas can realistically be used for reservoir expansion.  $c_{max}$  in equation 3g is derived for each basin by calculating the storage volume associated with the total available land area (see Appendix C Supplementary Methods 3). We followed the approach of a number of previous studies on renewable energy potentials<sup>102,103</sup> and define reservoir exclusion zones using maps of the following drivers: 1) population<sup>104</sup>; 2) cropland<sup>105</sup>; and 3) protected areas (Appendix C Supplementary Figure C-1 and Table C-1)<sup>106</sup>. We adopted dynamic population trajectories under two Shared Socioeconomic Pathways (SSPs) — SSP1 and SSP3. These scenarios were selected due to their opposing storylines about population growth and urbanization, which introduces human migration uncertainties into the analysis. SSP1 describes a future world with high urbanization and low population growth whereas lower urbanization and higher population growth define SSP3<sup>107</sup>. Total available land area for reservoir expansion in each basin is thus the remaining area outside the exclusion zones. Further discussion of the exclusions zones and the derivation is provided in Appendix C Supplementary Methods 3.

Other than population, agriculture, and protected land, other physical limitations such as elevation, slope and seismic risk will also constrain the available

area for reservoir expansions. It is important to further emphasize that this work does not prescribe actual sites for new reservoirs within basins, which requires a more detailed treatment of the local geography and stakeholder needs. To fully characterize exclusion zones, future work should consider direct use of high-resolution digital elevation model data and alternative metrics for limiting land availability. This study serves as a first-order estimation of reservoir storage and surface water yield expansion potential at global scale.

### **4.3 Results and Discussions**

#### **4.3.1 Impact of exclusion zones**

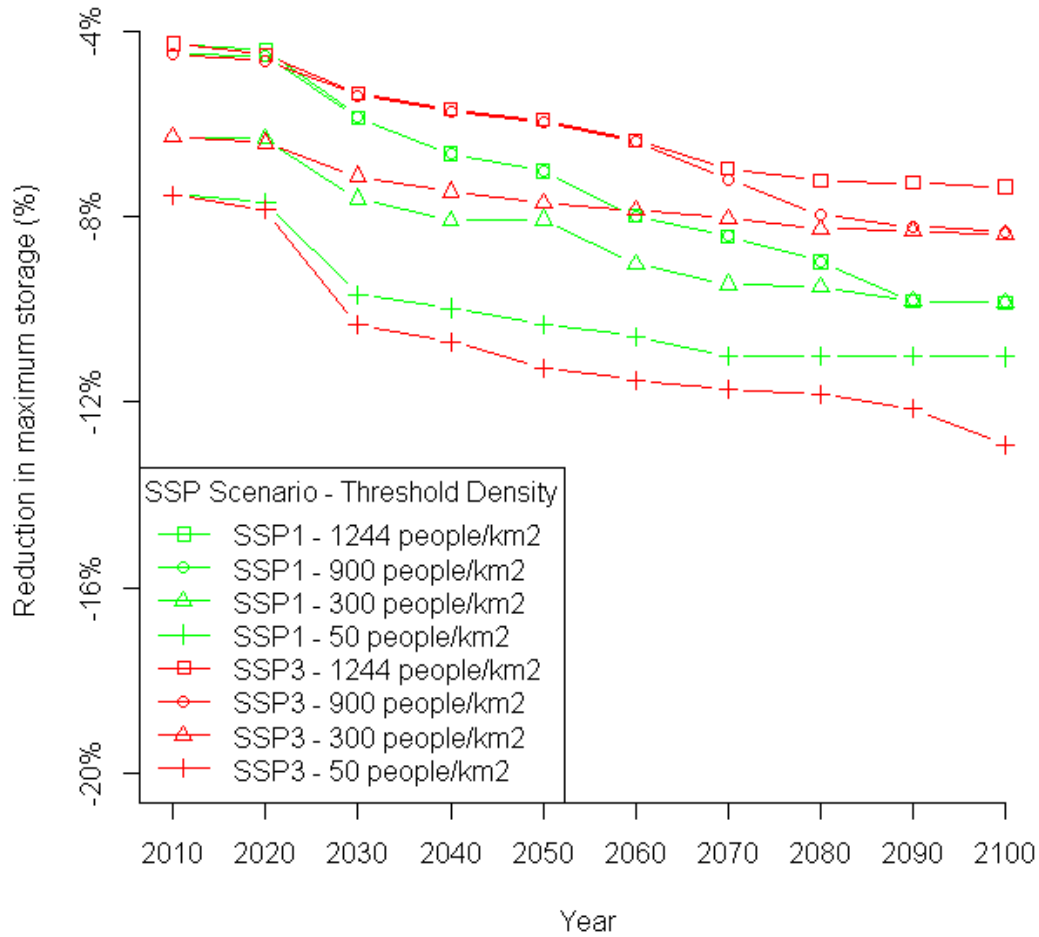
This study examined the impact of exclusion zones on reservoir storage potential for each basin by applying a sensitivity analysis where the following parameters are varied: 1) cutoff value for rural population density, below which grids cells are available for reservoir expansions, and 2) total population growth trajectory. The cutoff value is hypothetically assumed except for the maximum cutoff value in this sensitivity analysis (Appendix C Supplementary Methods 3). Parameter 1) and 2) will vary the total available land for reservoir expansion, and hence, the  $c_{max}$  variable in equation 3g.

Figure 4-2 shows the impact of exclusion zones on global reservoir storage potential while incorporating the sensitivity analysis on the cutoff value for rural population relocation. Overall, ~4% of reservoir storage potential would be unavailable because of pre-existing land occupations by cropland, protected land and urbanization, regardless of the differences in rural density cutoff value and population

development. Impacts on global reservoir storage potential also show an overall increasing trend over time, which corresponds to the decreasing available land due to increasing population trajectories under the two SSPs. Looking across different cutoff values, impacts on reservoir storage potential decrease with increasing cutoff value. This is because with a higher cutoff value, more grid cells become available for reservoir expansion, hence, reservoir storage potential is less constrained by land availability. SSP1 describes a future world with high urbanization and low population growth, therefore, more land is occupied by urban population and less land is available for reservoir expansion. SSP 3 depicts a world with lower urbanization and higher population growth, and therefore, is more rural land available for reservoir expansion. As a result, impact of exclusion zones on maximum storage is more significant under SSP1 than under SSP3. In conclusion, exclusion zones have important implications on the amount of global reservoir storage potential.

Overall, global maximum storage capacity is estimated to be ~5 times the current capacity volume (~6197 km<sup>3</sup>). However, due to exclusion zone constraints, reservoir storage potential is about 87-96% of estimated maximum storage capacity, which suggest that exploitable storage capacity is ~4.3-4.8 times the current storage capacity.





*Figure 4-2 Reduction in global maximum storage capacity due to socioeconomic development under different exclusion zone constraints.*

#### 4.3.2 Impact of climate change

Climate change impacts vary substantially from basin to basin (Appendix C Figure C-2) which highlights the significant geographical variability in terms of climate change impacts on hydrologic processes. Figure 4-3a shows the effect of climate change on the basin averaged net evaporative loss at a global scale under four different RCPs. On average, the net surface flux loss accounts for ~2.3% of the total annual firm yield. Differences among RCPs are minimal because the increases and decreases, in general, balance out when aggregated to the global scale. However,

there is a discernible difference in the trend of net evaporative loss over time, particularly for RCP8.5, which shows ~3.7% of net evaporative loss by the 2080s (Figure 4-3a). The range of differences between basins is expected to widen with climate change, indicating the importance of quantifying and understanding the spatial variability of net evaporative losses at the basin scale. Climate change mitigation is found to reduce the impacts of reservoir net evaporative loss at the global scale as nearly all basins would have <25% of change in net evaporative losses in the 2080s relative to the historical period via RCP2.6 (Figure 4-3b). As net surface flux from reservoirs is a non-trivial amount of water supply (~3-4%), these results further underscore the importance of exacerbating impacts from climate change in the context of reservoir management.

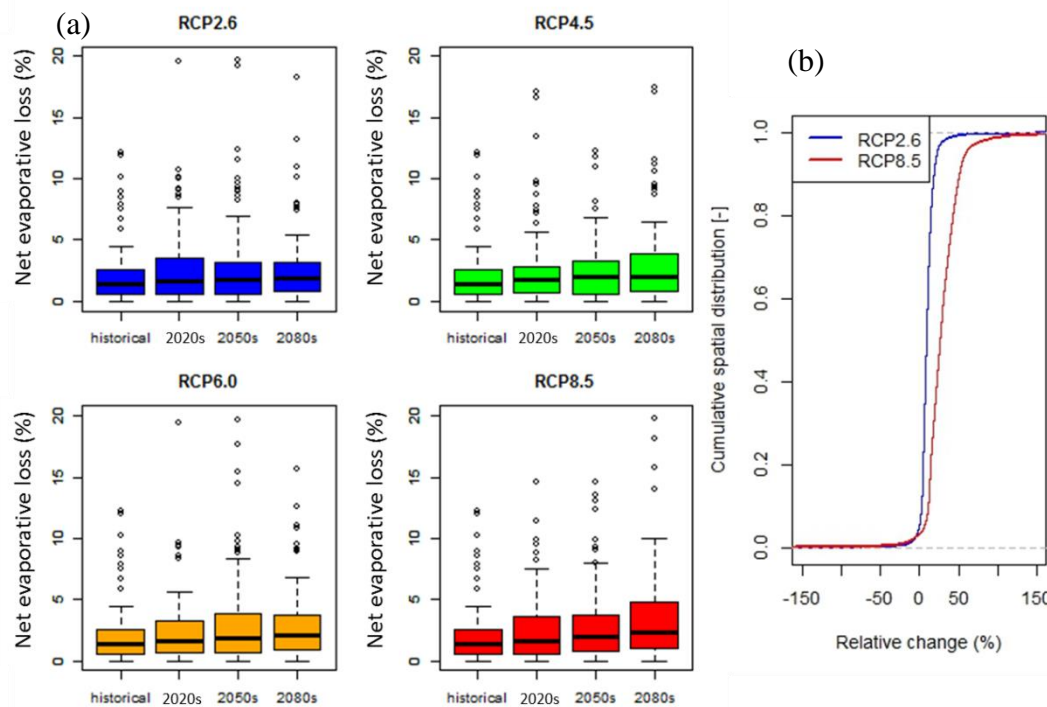
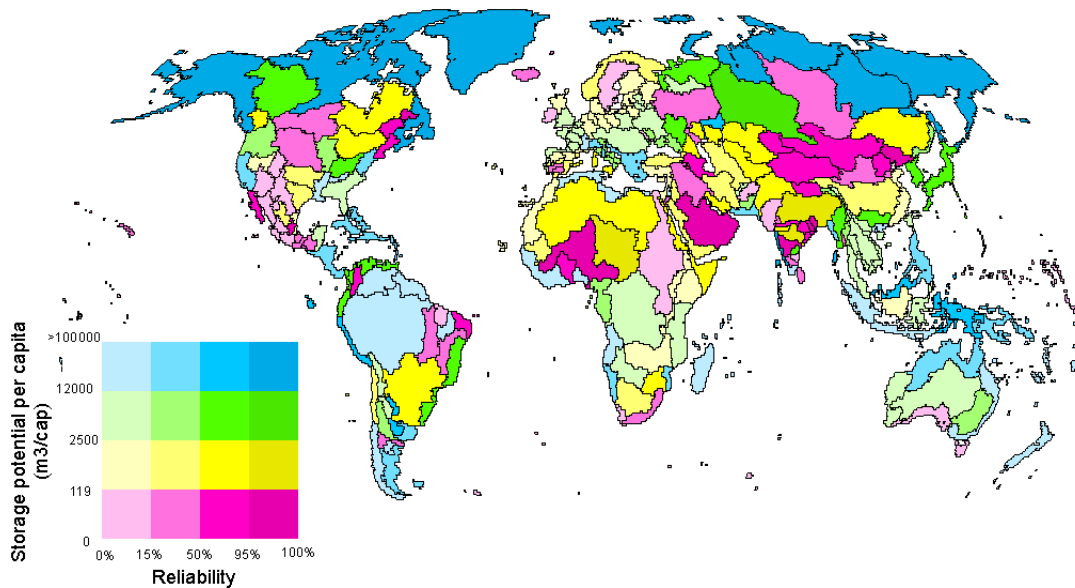


Figure 4-3 (a) Boxplot of net evaporative loss from reservoirs as percentage of total annual firm yield under four RCPs. The lower and upper limits of the box represent

*the 25<sup>th</sup> and 75<sup>th</sup> percentiles, respectively, while the whiskers extend to 1.5 times the interquartile range. The outliers extend to the most extreme outcomes. (b) Cumulative spatial distribution of change of net surface flux in the 2080s relative to the historical period under RCP2.6 and RCP8.5.*

#### 4.3.3 Integrated assessment

Figure 4-4 depicts the combined impacts of climate change and competing land-use activities on reservoir storage potential and reliability in the 2050s under a maximum reservoir expansion scenario. There are large disparities in the potential for reservoir expansion to provide firm yields across basins. For example, the majority of basins in Europe display greater than 2500m<sup>3</sup> of storage potential per capita, but relatively low reliability (<50%) for maintaining current firm yields due to the projected lower water availability under climate change. Basins in Asia show high reliability (>50%) for maintaining current firm yield yet relatively low storage potential (<2500 m<sup>3</sup>) per capita associated with large projections in population growth. Basins located at higher latitudes generally display abundant storage potential (>12000m<sup>3</sup>/capita), but these regions are not usually highly populated or water demanding; hence, there will likely be less of an incentive to plan for reservoir expansion in these regions. To quantify the necessity of building reservoirs to relieve regional water stress, it is necessary to integrate water demand from different sectors into this framework so that the reservoir expansion planning will take into account the severity of water scarcity as well as environmental and socioeconomic development factors.

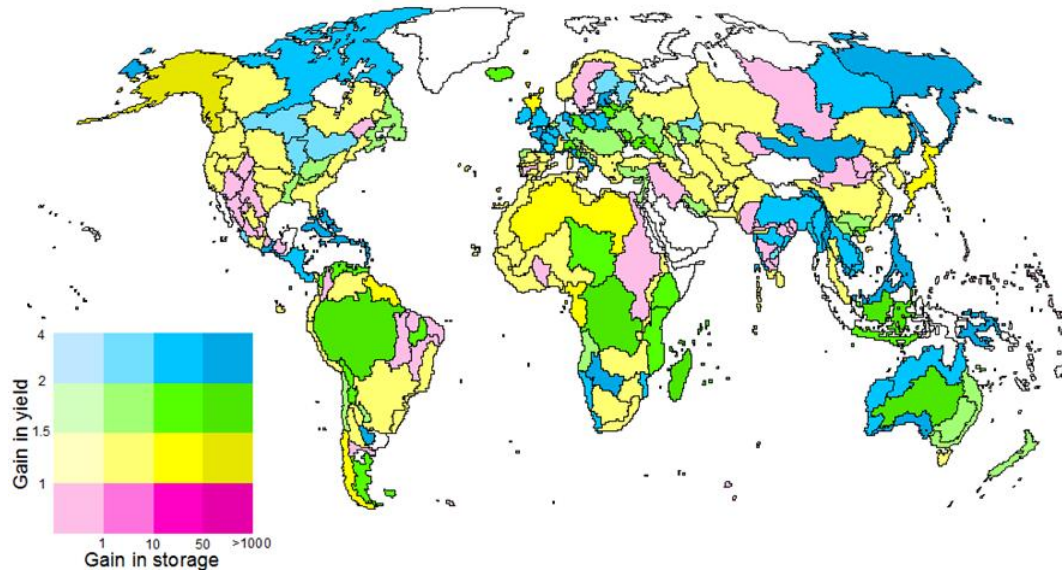


*Figure 4-4 Bivariate map showing reliability (with respect to current yields) and storage potential per capita by basin under SSP1 population trajectory in the 2050s*

Maximizing the additional amount of reservoir storage (~4.3-4.8 times greater) results in only a ~50% increase in firm yield worldwide due to the nonlinear shape of the S-Y curve (ex. Appendix C Figure C-3). Figure 4-5 shows the marginal gains vary substantially across basins. Gains in storage/yield are defined as the ratio between estimated maximum reservoir storage/yield and current reservoir storage/yield and it computed by analyzing the S-Y curve for each basin of interest. The majority of basins in North America have limited gain in yield by maximizing storage as these basins have already been highly developed. Basins in parts of India and Southeast Asia, on the other hand, display relatively greater marginal gain in yield by maximizing storage capacity.

By comparing the two types of map products in Figure 4-4 and Figure 4-5, we can identify regions where reservoir expansion will be particularly challenging. For example, current total reservoir storage capacity in the Missouri River Basin, U.S. is

133 km<sup>3</sup>. There is very little room for further expansion for the Missouri River Basin as the estimated storage potential is almost identical with current reservoir storage (Appendix C Figure C-3). Fully utilizing potential storage leads to negligible increases in firm yield, but with a high reliability of almost 100% due to the relative stability of future water availability under the tested scenarios (Appendix C Figure C-2). In Asia, current total storage capacity in the Mekong Basin is 19 km<sup>3</sup>, and the storage potential is about 351 km<sup>3</sup> (~18 times of current storage) (Appendix C Figure C-3b). In contrast, additional storage per capita for the Mekong Basin is 4200 m<sup>3</sup>/capita. By maximizing the potential storage, firm yield increases from 235 km<sup>3</sup> to ~500 km<sup>3</sup>, which is approximately 2 times the current firm yield. However, the reliability is estimated to be ~80% due to the projected lower reservoir inflows under climate change (Appendix C Figure C-2). As Figure 4-4 and Figure 4-5 illustrate, there exists large regional heterogeneity in marginal gain of yield when we fully utilize potential storage and the reliability of maintaining current yield varies from basin to basin. In addition to physical feasibility, there are other factors that constrain storage potential and hence gain in yield. A recent study by the Mekong River Commission tested a scenario of completing 78 dams on the tributaries between 2015-2030 the results of which suggested that it would have catastrophic impacts on fish productivity and biodiversity<sup>108</sup>. Therefore, it is critical to consider the trade-offs between socioeconomic progress and sustainable development when interpreting results with the tools built from this study.



*Figure 4-5 Bivariate map showing gains in yield/storage for each basin under the SSP1 population trajectory in the 2050s (blank regions indicate insufficient GRanD data)*

#### **4.4 Discussions and Conclusions**

This paper quantified the global potential for surface water reservoirs to provide firm yield across four different climate change scenarios and two socioeconomic development pathways under a maximum reservoir expansion scenario. Competing land-use activities are found to pose a nontrivial impact on reservoir storage potential worldwide. Approximately 4-13% of the estimated maximum storage capacity would be unavailable due to human occupation, existing cropland, and protected areas. In addition, net surface flux is non-trivial (~2.3% of total annual firm yield) and it is anticipated to increase ~3-4% under the most extreme climate warming scenario (RCP8.5). Importantly, the impact of climate change on reservoirs differs immensely from basin to basin, but the results of this analysis show agreement in terms of its negative role in reservoir reliability. International policies

aimed at reducing greenhouse gas emissions would help to reduce this uncertainty, and therefore point to additional co-benefits of climate change mitigation in terms of improving long-term water supply reliability.

Two types of bivariate map products were generated from this study to help decision makers understand the potential benefits of reservoir expansion at the basin scale and help define regional adaptation measures needed for water security. By linking this framework with anthropogenic water demand for various activities in each basin (e.g., agriculture, electricity, industry, domestic, manufacturing, mining, livestock), regions where water is severely in deficit could be identified, and thus, expanding reservoirs would potentially relieve regional water scarcity. Other than demand for water, alternative metrics that could presumably affect reservoir expansions include, but not are limited to, economic incentives, intuitional capacity, and infrastructure readiness.

This paper should not be seen as a call for more large dams, but rather an assessment of where policies and infrastructure investments are needed to sustain and improve global water security. In fact, dam removal activities have become more prominent in the United States since the 2000s, partly in concerns for river's deteriorating ecosystems and degraded environmental services<sup>109</sup>. In this study, we experimented with different augmentation factors for environmental flow to show how many basins have already installed storage capacity that exceeds presumed environmental guidelines. Table 4-1 shows the percentage of basins that could be overdeveloped if environmental flow requirements are increased.

Table 4-1 Percentage of basins overdeveloped with respect to environmental flow requirements

Environmental flow requirements (% of natural streamflow)	Percentage of basins overdeveloped (%)
10%	7
20%	11
50%	20
70%	98
90%	98

Results suggest that even at “poor or minimum” environmental flow condition<sup>110</sup> of 10%, a small portion of the world’s largest rivers have already installed storage capacity that put river’s ability to provide environmental services at risks. With increasing environmental flow guidelines, more river basins might fail to sustain the required environmental releases with the existing storage capacity. This has important implications for the current study as reservoir storage potential would be further constrained with more stringent environmental flow requirements.

This study serves as a valuable input to future work connecting water, energy, land and socioeconomic systems into a holistic assessment framework. Future effort will include other metrics described above to further constrain reservoir storage potential. Future work could also examine sensitivity of the results to a wider range of GHMs and GCMs to better capture model uncertainty. Finally, the results of this study provide planners with important quantitative metrics for long-term water resource planning and help explore the implications through integrated modeling of water sector development.



## Chapter 5 Conclusions and Future Directions

This Ph.D. dissertation explored three important research questions pertaining to the water-energy-climate nexus:

1) How vulnerable is the current U.S. thermoelectric power generation system to changes in climate? 2) How is the U.S. electricity system going to adapt to constraints on water availability? 3) What is the surface water reservoir expansion potential for major hydrologic basins around the world?

For the first question, results from Chapter 2 suggest that climate change impacts on U.S. thermoelectric power plants are not as severe as suggested by previous studies. This is because earlier modeling studies did not include a spatially-disaggregated representation of environmental regulations, as practiced in the U.S., which grant provisional variances that temporarily relieve power plants from permit requirements. Hence, thermoelectric power plants in the U.S. are not as vulnerable to climate change as previously thought. **Findings from this part of the study highlight the importance of legal constructs in climate change impact assessment.**

For the second question, results from Chapter 3 anticipate substantial capital stock turnover of the energy system, if water availability is severely constrained in the U.S. Such an outcome could result in non-negligible economic costs for the U.S., particularly for the western states, as water-intensive technologies such as coal- and gas-fired power plants would be forced to go offline and less water-intensive technologies, such as wind and solar photovoltaic, would need to be elevated to meet the energy demand. **These results call for the integration of water availability**

**constraints into electricity capacity planning to avoid costly adaptation of the energy system in the future.**

For the third question, results from Chapter 4 indicate that regions where reservoir storage can be expanded worldwide are largely restricted by land-use, human development and climate change, in addition to different environmental flow requirements that substantially affect the marginal gains in reservoir storage and water supply. As a first-order assessment of where policies and infrastructure investments are needed to sustain and improve global water security, **this study serves as a valuable input to relevant future work connecting water, energy, land and socioeconomic systems into a holistic assessment framework.**

The three studies are distinctive in their own scope and approach; however, they are tied in to one another through the flow of vulnerability to adaptation. The first study assesses U.S. energy system's vulnerability to water availability and water temperature, followed up by the second study that assesses the adaptive capacity in the U.S. energy supply sector to water availability constraints, and the third study extends the study scale to the rest of the world and provides one possible adaptation measure in water supply sector that may alleviate some of the energy-water conflicts described in the first and second study.

**The over-arching message from this dissertation is that interrelationships between water, energy and climate are complex and evolving. Decision makers should consider and work towards integrating these complexities into future resource planning so that the society may be more resilient to future changes and uncertainties.** Failure to do so has already led to costly amendments and will

continue to cause more economic costs if our decision-making landscape remains unchanged<sup>11</sup>.

The challenges in the water-energy-climate nexus policy are not unique to any single country in the world. Many countries around the world are facing similar water-energy related conflicts and they are actively seeking solutions to ensure the country's energy and water security. For example, China is rich in coal and heavily relies on coal-fired technologies to generate electricity, but the water resources in coal mining regions in China are scarce and severely limit large-scale deployment of coal-based power plants<sup>111</sup>. Due to concerns for air pollutions along with a mix of concerns including water stress, China central government has emphasized domestic unconventional gas development as an adaptation strategy for national energy security<sup>112</sup>. For similar reasons, China constructed the world's largest hydroelectric dam—The Three Gorges Dam that provides electricity and regulates water supply for downstream provinces, although its long-term environmental consequences and socioeconomic impacts remained controversial.

The decision-making landscape for the nexus is fragmented, complex, and changing. Furthermore, the incentive structures are overlapping but not necessarily consistent. For example, water right in the U.S. is inherently managed at the state or local level and the allocation doctrines vary substantially from East to West. But water basins do not follow political jurisdictions, and thus, multi-jurisdictional issues are very common in water resources management. Energy policies also have variations across states, so are the environmental regulations on thermoelectric water intake and discharge. Because of the inherent institutional inconsistency, an

integrated approach to the interconnected energy and water systems should be adopted to address challenging issues in both domains.

This dissertation is not without limitations. In general, the three studies presented here are built upon modeling experiments with validation against observations, and hence, model selection and model sensitivity become an important source of uncertainty. In the first study, data input into TPGM included water temperature and natural streamflow produced by CLM-MOSART. Only one land surface model (out of many available) is selected because of high computational cost for simulation. Choosing a different land surface model could have produced different inputs which could further change TPGM's responses. However, historical water temperature and natural streamflow produced by CLM-MOSART have been validated spatially and temporally against gauge observations, projections of hydrologic variables by CLM-MOSART provide one possible scenario of future climate change impact. In a similar manner as choosing a different land surface model, using a different GCM driving CLM-MOSART could also result in large variations in TPGM's output. This is because previous studies have shown that global disagreement among different GCMs exhibit larger uncertainty than among different GHMs or land surface models<sup>113,114</sup>. The same argument is relevant to the third study in which only one GCM-GHM combination is selected. Future research could include experimenting with different GCMs and different climate change mitigation scenarios, but it is outside the scope of current dissertation to analyze full spectrum of model uncertainty.

Another important source of uncertainty originates from treatment of future commodities and climate conditions. The first study focuses the entire analysis on existing energy infrastructure with implicit assumptions that new energy infrastructure would remain on the same geographic locations as existing ones retire. In the second study, only one adaptation strategy is investigated (e.g., fuel mix) while there are other alternatives that could also lead to meeting the constraint target. The third study only examines the effect of three types of exclusion zones while there could be other constraint rules that can better constrain results associated with institutional capacity. In addition, only two climate change mitigation scenarios (e.g., RCP4.5 and RCP8.5) are examined in the first and third study. These two scenarios serve to represent a range of future climate conditions where RCP4.5 represents the greenhouse gas emission reduction world while RCP8.5 represents the “business as usual” scenario. Further, assumptions about future technological evolution, economy, population, climate, policy, land use, and many other factors may substantially modify results drawn from this dissertation. Despite the uncertainties around model selection and future scenarios, this dissertation describes some likely scenarios of future energy and water system evolution and provides possible solutions in face of possible future changes.

In addition, there are many alternative adaptation strategies that are broadly adopted to alleviate energy-water conflicts, and in this dissertation, we have only focused on some possible solutions in energy supply (e.g., capital stock turnover) and water supply (e.g., reservoir capacity expansion) sector. Adaptations in energy and water demand sector are also widely discussed and practiced worldwide, and could

alleviate pressures on both water and energy systems as well as on the environment<sup>1,14</sup>.

In light of limitations in this dissertation, areas of improvements subject to future work may include but is not limited to 1) investigating adaptation strategies in energy demand and water demand sector (i.e., resource efficiency improvement); 2) developing a more inclusive framework that incorporates water supply from unconventional sources (i.e., reclaimed water, seawater, and saline water); 3) enabling market-based technology and resource adoptions that allow for dynamic competitions; 4) incorporating adaptation strategies in the demand sector; 5) developing decision making tools for policy formulation, concerning investment in energy and water infrastructure; and 6) expanding the scope to integrate other sectors (i.e. agriculture, industry, domestic, manufacturing, mining, and livestock) and that may be further contributing to and complication our understanding of the water-energy-climate nexus.

## Final Remarks

I would like to take this opportunity to use my dissertation as a platform to not only share my research findings, but also some personal visions. I have been very fortunate to have worked with scientists that contributed to the monumental IPCC Annual Report, and to witness the historic moment of the passing of the Paris climate accord. As much as I've enjoyed building models and analyzing data, I have realized disconnect between academic research and policy formulation has long existed and a substantial amount of effort is further needed to integrate science and policy, so that scientists can make a greater impact beyond academia. We need to strengthen scientists' role in advising the nation by merging science and policy. After I leave Maryland, I hope to take my degree to the next level and become part of the solutions that can positively affect the current directions of my field. I hope to become part of the driving force behind science-policy integration and to continue my passion in implementing climate change mitigation and adaptation.

# Appendices

## Appendix A

### Supplementary Figures

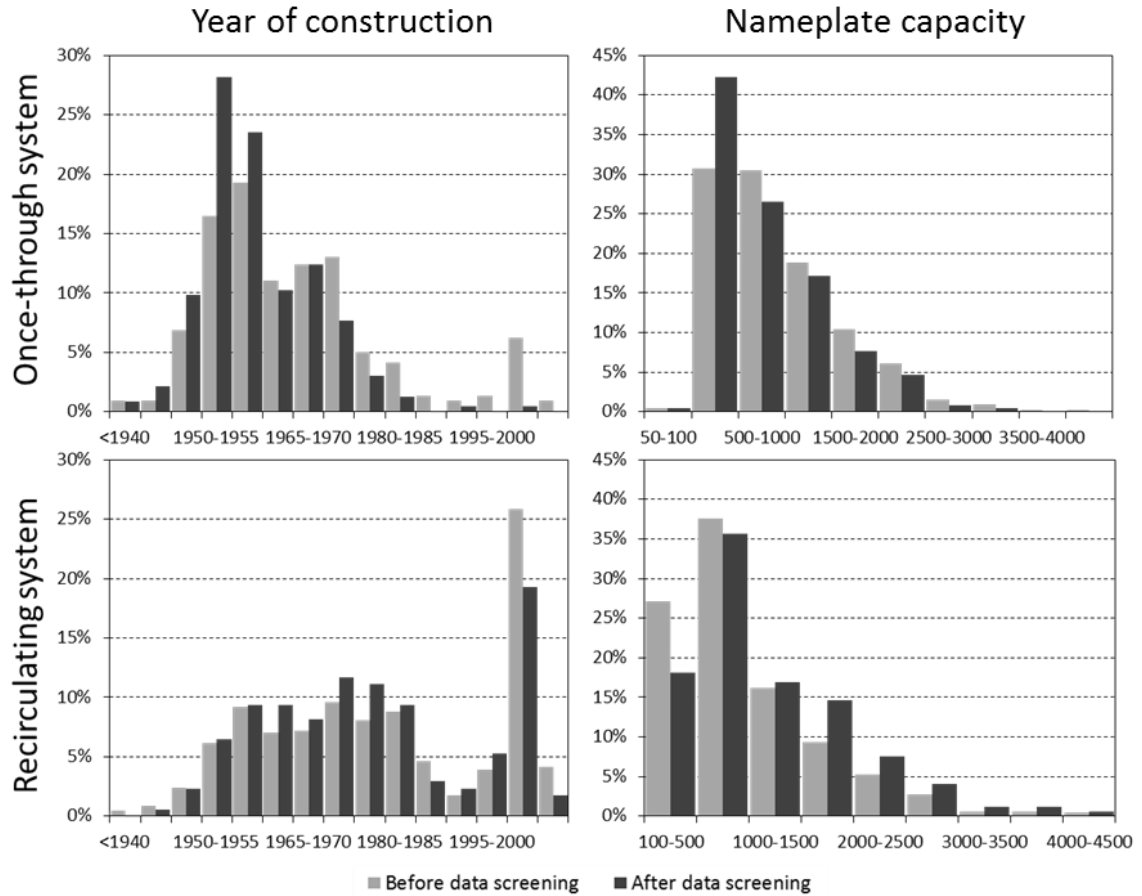
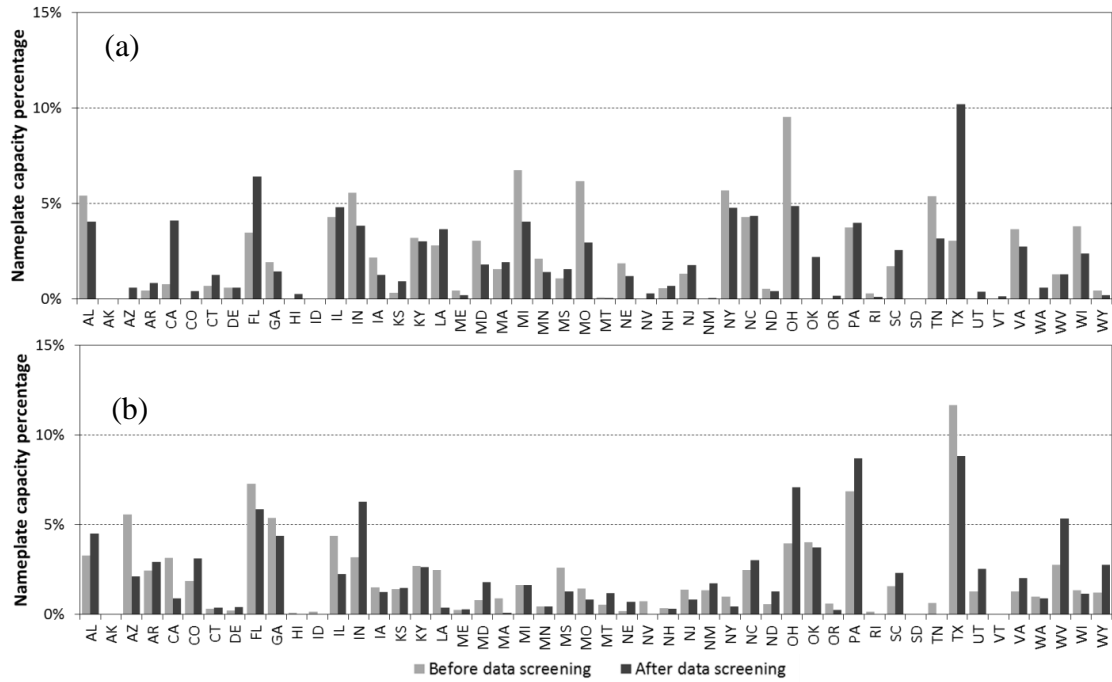


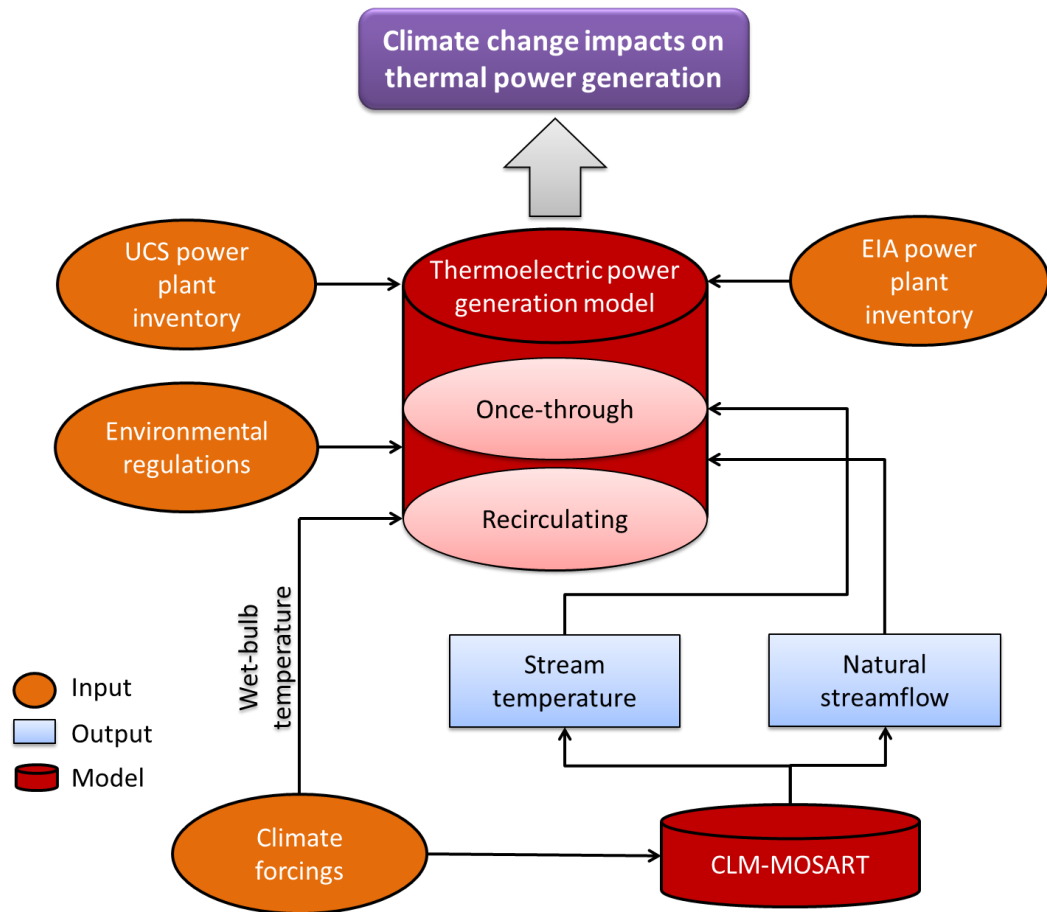
Figure A-1 Distribution of thermoelectric power plants' year of construction and nameplate capacity (data screening process is described in Supplementary A Methods

2)





*Figure A-2 State aggregated nameplate capacity percentage (%) as of U.S. total nameplate capacity for (a) once-through systems and (b) recirculating systems before and after data screening.*



*Figure A-3 Structure of coupled land surface model and thermoelectric generation model*

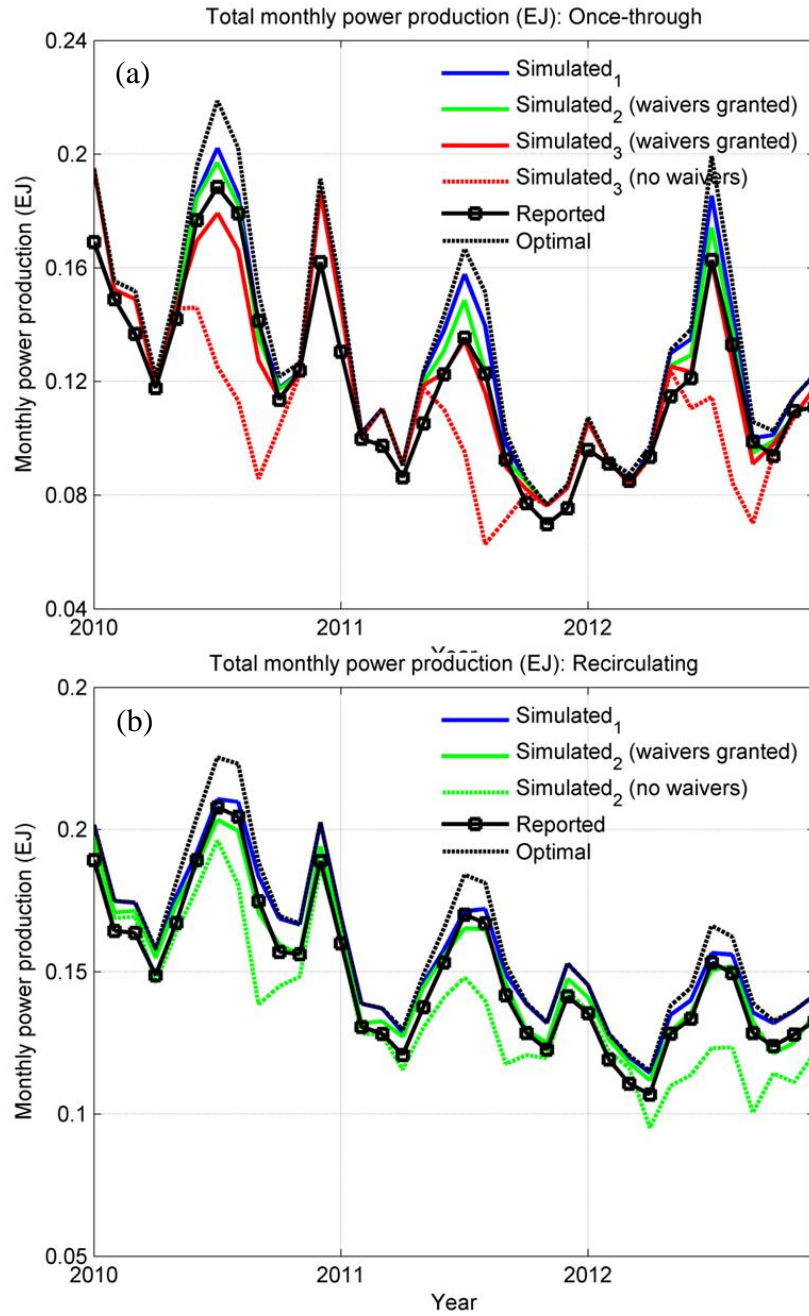
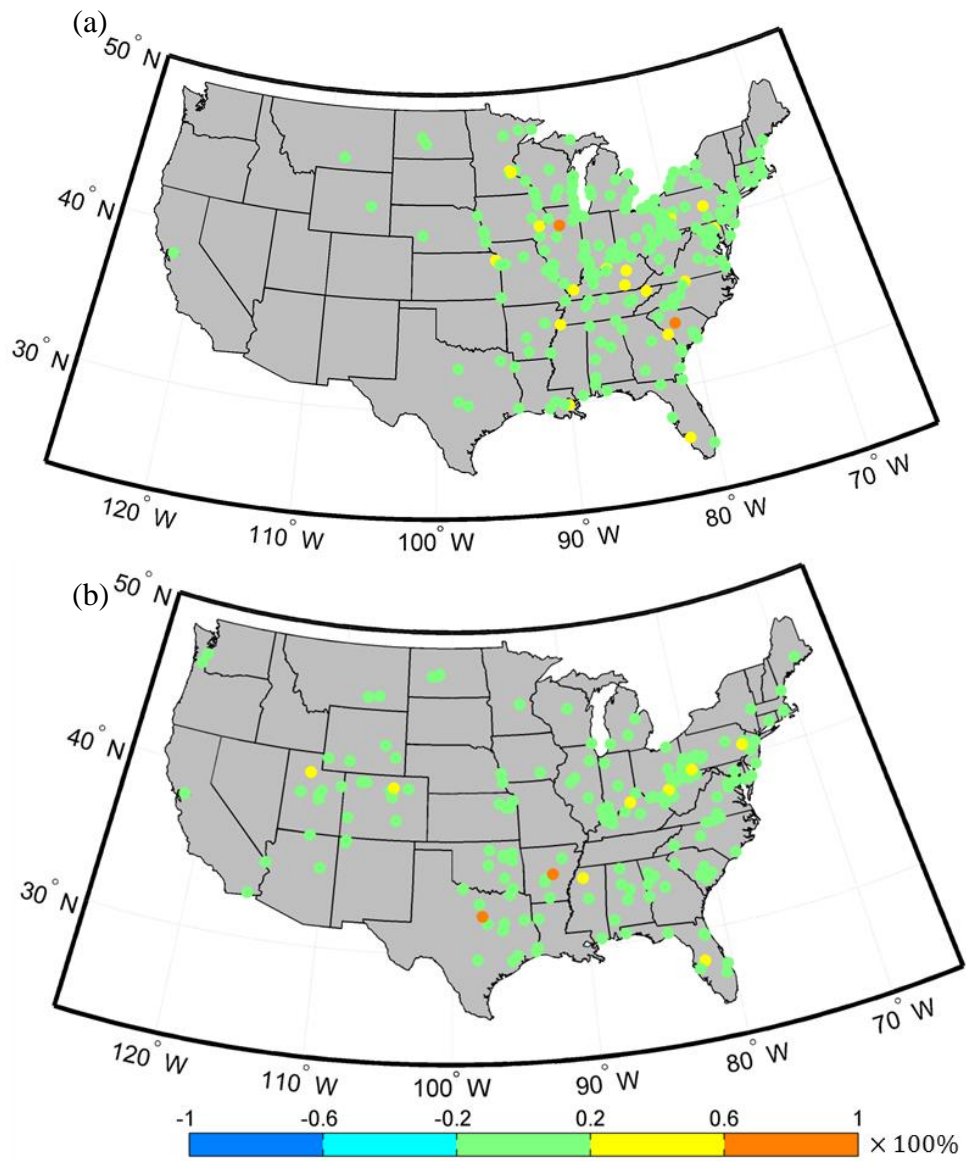


Figure A-4 Simulated monthly power production considering different constraints and observational monthly power production for (a) once-through systems and (b) recirculating system



*Figure A-5 Relative difference between simulated and reported power production during 2010-2012 for (a) once-through systems and (b) recirculating systems*

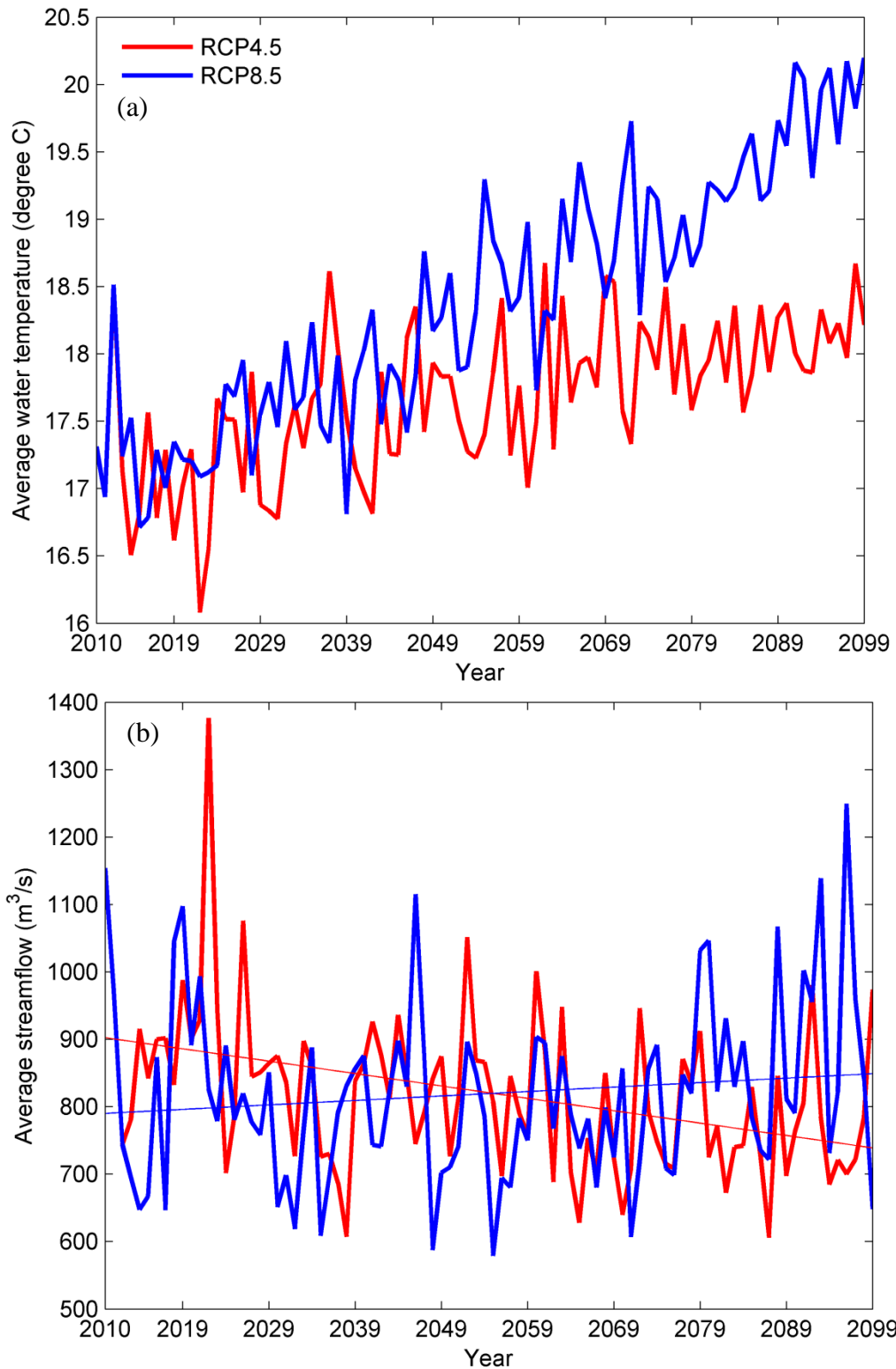
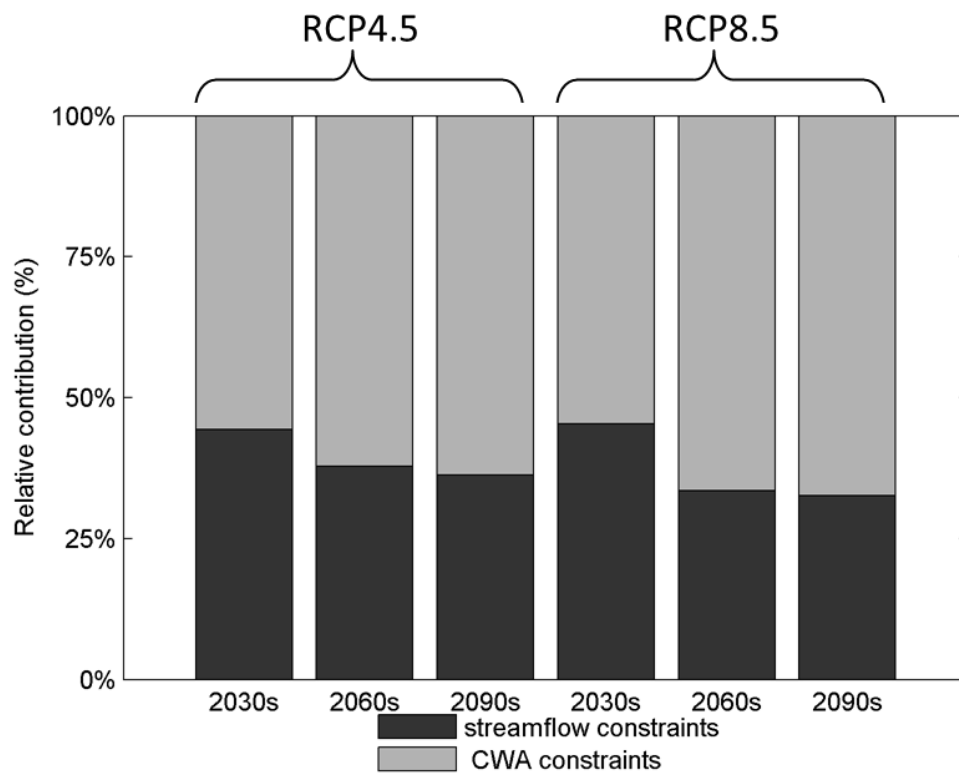


Figure A-6 (a) Water temperature averaged over all selected once-through power plant locations in the U.S. (b) Annual streamflow averaged over all selected power plant locations in the U.S.



*Figure A-7 Relative contribution to reduction in usable capacity for once-through systems*

## Supplementary Tables

Table A-1 Environmental flow guidelines for base flow regimes using the Tennant

Method

<b>Description of flows</b>	<b>October through March</b>	<b>April through September</b>
Flushing or maximum	200%	200%
Optimum range	60-100%	60-100%
Outstanding	40%	60%
Excellent	30%	50%
Good	20%	40%
<b>Fair or degrading</b>	<b>10%</b>	<b>30%</b>
Poor or minimum	10%	10%
Severe degradation	0-10%	0-10%

Table A-2 EPA state water temperature standards criteria summary

<b>State</b>	<b>Maximum temp. in fresh water streams (°C)</b>	<b>Daily maximum temp. rise of fresh water streams from ambient water temperature (°C)</b>	<b>Daily thermal variance (°C)</b>	<b>Note</b>
<b>Alabama</b>	32.0	2.8		
<b>Alaska</b>	25.0			
<b>Arizona</b>	32.0	3.0		
<b>Arkansas</b>	32.0	2.8		Maximum allowable water temperature obtained from Arkansas Pollution Control and Ecology Commission
<b>California</b>	32.0	2.8		
<b>Colorado</b>	20.0/30.0	3.0		20.0 °C for cold water biota and 30.0 °C for warm water biota. Adopted 30.0 °C.
<b>Connecticut</b>	29.4	2.2		
<b>Delaware</b>	29.4	2.8		

<b>Florida</b>	32.0/33.0	2.8		Unlike other states, Florida constrains discharging temperature instead of temperature after mixing. 32.0 °C is the maximum discharge temperature for latitude 30.0 degrees N and 33.0 °C is for latitude 30.0 degrees S, and 2.8 °C is the maximum temperature rise for discharge effluent
<b>Georgia</b>	32.0	2.8		
<b>Hawaii</b>	32.0	1.0		
<b>Idaho</b>	19.0/29.0	1.0/2.0		19 °C and 1.0 °C (max T & delta T) for cold water biota, and 29 °C and 2.0 °C for warm water biota. Adopted the latter.
<b>Illinois</b>	32.0	2.8	1.7	
<b>Indiana</b>	32.2	2.8	1.7	The maximum in summer in most streams does not exceed 32.2 °C. Maximum limit beyond limit is 1.7 °C.
<b>Iowa</b>	32.0	3.0/2.0		3.0 °C for interior streams or the Big Sioux River and 2.0 °C for cold water fisheries. Adopted 3.0 °C.
<b>Kansas</b>	32.0	2.8		
<b>Kentucky</b>	31.7			31.7 °C is the instantaneous maximum.
<b>Louisiana</b>	32.2	2.8		
<b>Maine</b>	29.0	2.8		
<b>Maryland</b>	32.0			
<b>Massachusetts</b>	28.3/20.0	2.2		28.3 °C for warm water fisheries and 20.0 °C for cold water fisheries. Adopted 28.3 °C.
<b>Michigan</b>	29.4	2.8	2.8	
<b>Minnesota</b>	30.0/32.0	2.8		30.0 °C for Class B and 32.0 °C for Class C fisheries and recreation. Adopted 32.0 °C.
<b>Mississippi</b>	32.0	2.8		
<b>Missouri</b>	32.0	2.8		
<b>Montana</b>	29.0	1.7		
<b>Nebraska</b>	32.0/22.0	3.0		32.0 °C for warm water and 22.0 °C for cold water. Adopted 32.0 °C.
<b>Nevada</b>	34.0	3.0		34.0 °C for non-trout waters



				based on class
<b>New Hampshire</b>	28.3/20.0	2.8		28.3 °C for warm water fisheries and 20.0 °C for cold water fisheries. Adopted 28.3 °C.
<b>New Jersey</b>	30.6	2.8		
<b>New Mexico</b>	20.0/32.2	2.7		20.0 °C for cold water and 32.2 °C for warm water. Adopted 32.2 °C.
<b>New York</b>	32.0	2.8		32.0 °C for non-trout waters.
<b>North Carolina</b>	32.0	2.8		
<b>North Dakota</b>	29.4	2.8		
<b>Ohio</b>	31.7			
<b>Oklahoma</b>	34.4	2.8		
<b>Oregon</b>	32.0			
<b>Pennsylvania</b>	32.0	2.8		
<b>Rhode Island</b>	28.3/32.0	2.2		28.3 °C for class B and 32.0 °C for class D. Adopted 32.0 °C.
<b>South Carolina</b>	32.2	2.8		
<b>South Dakota</b>	32.2	2.8		
<b>Tennessee</b>	30.5	1.7		
<b>Texas</b>	35.0	2.8		
<b>Utah</b>	20.0/27.0	2.0/4.0		20.0 °C / 2.0 °C (max T / delta T) for Class A, 27.0 °C / 4.0 °C for Class B and C. Adopted 27.0 °C / 4.0 °C
<b>Vermont</b>	32.0	0.56		
<b>Virginia</b>	32.0	3.0		
<b>Washington</b>	24	0.3		
<b>West Virginia</b>	30.6/22.8	2.8		30.6 °C for May through Nov, and 22.8 °C for Dec through Apr. Adopted 30.6 °C.
<b>Wisconsin</b>	32.0	2.8		
<b>Wyoming</b>	32.2/25.6	2.2/1.1		32.2 °C / 2.2 °C (max T / delta T) for warm water and 25.6 °C / 1.1 °C for cold water. Adopted 32.2 °C / 2.2 °C.
<b>District of Columbia</b>	32.2	2.8		

Table A-3 Descriptions of different simulation scenarios

Constraints	Scenarios					
	Optimal	Simulated <sub>1</sub>	Simulated <sub>2</sub> (with waivers)	Simulated <sub>2</sub> (without waivers)	Simulated <sub>3</sub> (with waivers)	Simulated <sub>3</sub> (without waivers)
Inlet ambient temperature	-	X	X	X	X	X
Available streamflow	-	-	X	X	X	X
Clean Water Act 316(a)	-	-	-	-	X	X
Provisional waivers granted			X	-	X	-

Table A-4 Comparison of methodology with similar studies

Studies Comparisons		van Vliet et al. (2016)	Bartos and Chester (2015)	This study
<b>Modeling framework</b>	Hydrological model	Variable Infiltration Capacity (VIC)	Variable Infiltration Capacity (VIC)	Community Land Model (CLM)
	Routing model	DDM30 routing network based on Döll and Lehner <sup>115</sup>	Lohmann et al. <sup>116</sup>	Model for Scale Adaptive River Transport (MOSART)
	Reservoir operation model	SCEM-UA algorithm described by Haddeland et al. <sup>117</sup>	None	None
	River temperature model	RBM	RBM	Li et al. <sup>118</sup>
	Electricity model	Hydropower: Hydrostatic equation Thermoelectric:	Hydropower: Hydrostatic equation Steam OT:	Thermoelectric OT and RC: Miara and Vörösmarty <sup>22</sup>

		van Vliet et al. <sup>20</sup>	modified van Vliet et al. <sup>20</sup> Steam RC: a combination of physically based heat and mass balance equations  Combustion turbine: a combination of energy balance equations  Solar: Dubey et al. <sup>119</sup>  Wind: Royal Academy of Engineering	
<b>Model resolution</b>		Daily 0.5°×0.5°	Daily 1/8 degree	Daily 1/8 degree
<b>Study region</b>		Global	Western Electricity Coordinating Council (WECC) – Western U.S.	Continental U.S.
<b># of power plants</b>	Hydro dams	24,515 (78% of total hydropower capacity)	978 vulnerable electric power stations in total	None
	Thermoelectric plants	1,427 (28% of total thermoelectric power installed)		234 thermoelectric plants with OT cooling and 171 with RC cooling (~44% of installed capacity)
	Renewables	None		None
<b>Power plant data source</b>		- World Electric Power Plant Database (WEPPD) (Platts)	EIA and UCS	EIA and UCS

	- Carbon Monitoring for Action database - Socioeconomic Data and Application Center database		
<b>GCMs</b>	5 GCMs: MIROC, IPSL, HADGEM, GFDL and NORESM	2 GCMs: UKMO-HADCM3.1 and MPI-ECHAM5.3	1 GCM: RESM
<b>Future scenarios</b>	RCP2.6 and RCP8.5	A1B, A2 and B1	RCP4.5 and RCP8.5
<b>Assumption of environmental flow</b>	Not explicated stated	Tennant Method	Tennant Method
<b>Assumption of outlet temperature</b>	N/A	N/A	From EPA, varied by state
<b>Assumption of discharge temperature</b>	US coal: National Energy Technology Laboratory Coal Power Plant Database  Rest of the world and US other fuels: extrapolated from $T_{max}$ , stream temperature and mean streamflow relationship	EIA923  If no data entry, assume 32°C	EIA923
<b>Model validation (estimated capacity with reported)</b>	Normalized bias mostly between -25% and 25% (aggregated to country level)	None	Normalized bias mostly between -20% and 20% for each power plant
<b>Adaptation scenarios</b>	- Increase efficiency - Change fuel - Switch to cooling tower - Switch to seawater cooling	None	None

	- Replace top vulnerable with seawater and dry cooling		
<b>Assumption of future installation</b>	None	None	None
<b>Major scientific merit</b>	First global assessment Model validation	Included renewable energy	More detailed representation of environmental regulation  Model validation and parametrization

## Supplementary Methods

### 1. Data Descriptions

The Energy Information Administration (EIA) maintains a database of power plants inventory in the United States. Form EIA-860 (<https://www.eia.gov/electricity/data/eia860/>) collects data on the status of existing electricity generation plants and their associated equipment (including generators, boilers, cooling systems, and flue gas desulfurization systems) in the United States. Information collected by EIA-860 that are used in the model include plant ID, geographic location, generator type, fuel type, operating status, nameplate capacity, and water flow rate at 100% capacity. EIA-860 data from 2010 to 2012 were collected for this study.

Form EIA-923 (<https://www.eia.gov/electricity/data/eia923/>) collects detailed electric power data at both monthly and annual time steps. Information used as model inputs include cooling system type, hours in service, monthly cooling water

withdrawal rate, monthly average intake water temperature, monthly average discharge water temperature, monthly heat input, and monthly net generation. EIA-923 monthly and annual surveys from 2010 to 2012 were collected for this study. Only three years of the historical records were used here since only three years of overlap exist between EIA-923 monthly data and CLM-MOSART historical simulation. EIA-923 data prior to 2010 were recorded at annual time step.

Union of Concerned Scientists (UCS) maintains a publicly available database of power plants. The UCS EW3 database (<http://www.ucsusa.org/clean-energy/energy-water-use/ucs-power-plant-database#.WSHnxmjvIU>) provides information on the reported water source type for power plant cooling with matching plant ID used by EIA as well as first year of operation of the power plants. This dataset includes data only up to 2008, but since we do not expect power plants changing their sources of cooling water between 2008 and 2012, and installed fossil fuel capacity only increases from 770 gigawatts in 2008 to 781 gigawatts in 2012, the existing thermal power plants in UCS EW3 should be representative of thermal power plants up to 2012.

## 2. Data Screening

UCS EW3 includes over 4000 power plants in its database. 442 of the power plants are identified using once-through cooling technology (416 gigawatts of total nameplate capacity) and 471 are identified using recirculating cooling (457 gigawatts of total nameplate capacity).

Initial screening was performed on EIA-860 and EIA-923 data to select power plants that meet the following criteria:

- Geographic locations lie within continental U.S.
- Operation status shows “in service”
- Generation type is not cogeneration
- Identified as thermal generation type
- Generation technology is either steam engine or combined cycle
- Cooling technology is once-through cooling or recirculating cooling (exclude dry cooling and hybrid cooling)
- Use fresh surface water (exclude ponds, lakes, reservoirs and groundwater)

After initial data screening, 234 plants remained with once-through cooling systems (182 gigawatts of total nameplate capacity) and 171 power plants remained with recirculating cooling systems (200 gigawatts of total nameplate capacity), which in total accounts for ~44% of the existing thermoelectric capacity. A number of power plants with unrealistic data entries for discharge water temperature and intake water temperature were also identified and removed from the data sample.

Comparisons were done to ensure the representativeness of the selected sample (Supplementary Figure A-1 and Supplementary Figure A-2). Over 70% of the once-through power plants were built between 1950 and 1975 while the construction for recirculating systems peaked in early 2000. The distribution of years of construction for the selected sample is comparable with the distribution prior to data screening. The distribution of nameplate capacity before and after data screening is similar with over 50% of the capacity between 100 megawatts to 1000 megawatts for both cooling systems (Supplementary Figure A-1). Geographical distribution of the

selected sample also displays pattern similar to distribution of data prior to screening for both cooling systems (Supplementary Figure A-2). Therefore, it is reasonable to say that the selected sample is representative of the corresponding type of power plants in EIA inventory.

### 3. Modeling Framework

Numerous studies<sup>20,23,25</sup> employ modeling frameworks that couple a hydrological model that includes a stream temperature thermodynamics with a thermoelectric generation model that includes technological details at the power plant level. The complexity of the hydrological components in these coupled models ranges from a relatively simply air-water relationship<sup>120</sup> to process-based stream temperature routines<sup>20,23,25</sup>. The thermoelectric production modeling component is essentially based on thermodynamic equations, which distinguishes between different cooling technologies and incorporates plant specific details. These coupled models are usually resolved at the plant level and include many fixed assumptions. Alternatively, Greis et al.<sup>19</sup> took a “system dynamics” approach and demonstrated the capability of the model using a single hypothetical thermoelectric power plant. Miara and Vörösmarty<sup>36</sup> developed the Thermoelectric Power & Thermal Pollution Model (TP2M) with distinctions between different cooling and generation technologies and demonstrated modeling capability on hypothetical power plants.

In this current study, we constructed a coupling framework that links the community land model (CLM)<sup>121</sup> with a thermoelectric power generation model (TPGM) (Supplementary Figure A-3). Inputs into TPGM include streamflow temperature and natural streamflow simulated by CLM, wet-bulb temperature



computed from the available air temperature and humidity, power plant information from EIA and UCS, and environmental regulations compiled from EPA guidance. TPGM includes both once-through systems and recirculating systems. We use a single global (CESM) and regional (RESM) climate models in order to reduce computational expense and to maintain a tractable project scope. Also the seasonal and spatial patterns of wet/dry trends from the global and regional models are broadly consistent with the Coupled Model Intercomparison Project Phase 5 (CMIP5) multi-model ensemble<sup>122</sup>.

### 3.1 CLM-MOSART

A large-scale stream temperature model was recently developed<sup>123</sup> in CLM<sup>121</sup> as part of the Community Earth System Model (CESM). The stream temperature model was validated against observations from over 320 USGS gauge stations. Results demonstrate the model is capable of capturing the spatial and temporal variations of stream temperature in the U.S.<sup>123</sup>. Runoff fluxes simulated by CLM are routed spatially using a physically based river-routing model called the Model for Scale Adaptive River Transport (MOSART)<sup>124</sup>. The coupled CLM-MOSART framework was evaluated globally using observed streamflow<sup>125</sup> and over the United States using observed stream temperature<sup>123</sup>. Streamflow and water temperature simulations display high agreement with the USGS gauge observations<sup>123,126</sup>. Note, the CLM-MOSART model used in this study does not represent the impacts of water management activities such as reservoir operation and local surface water withdrawal. Including these impacts in CLM-MOSART streamflow and water temperature simulation will make it difficult to explicitly dissect climate change impacts on

thermoelectric power generation from many other driving forces, such as upstream water use activities.

Stream temperature and natural streamflow were simulated using CLM-MOSART from the historical period 2010-2012 using meteorological boundary conditions defined by the North American Land Data Assimilation System stage II (NLDAS2), and for the future period 2013-2100 driven by the forcing derived with a combination of a Regional Earth System Model (RESM)<sup>127</sup> and bias correction under two climate scenarios, RCP4.5 and RCP8.5. Only three years of historical period (2010-2012) were selected because there are only three years of overlap between EIA-923 monthly data and CLM-MOSART historical simulations. Outputs are at a spatial resolution of 1/8 degree and daily temporal resolution. For each power plant sitting within the 1/8 degree grid, daily stream temperature and natural streamflow data for the historical period and the two different RCPs scenarios were extracted for subsequent analysis discussed further below. When more than one power plant is contained within the same 1/8th degree grid, we assume that they share the same stream characteristics and as defined by the mode, but do not interact with each other.

### 3.2 Thermoelectric Power Generation Model (TPGM)

The thermoelectric power generation model simulates usable capacity and thermal effluents for all thermoelectric power plants in the U.S. that use evaporative cooling systems, including once-through and recirculating systems. Further, the cooling water source is from surface streamflow, excluding lakes, ponds, groundwater, and saline water. The modeling approach is adopted from Miara and Vörösmarty<sup>22</sup> and applied to 405 thermoelectric power plants in the US. The TPGM

accounts for three main factors that can influence power production in the context of a changing climate.

Inlet ambient temperature: If water temperatures at the inlet of power plants are above optimal conditions, it will result in lower generation efficiency. This is because a high cooling water inlet temperature increases the condensing temperature and saturated pressure of the steam coming from the turbine, which leads to a smaller temperature gradient between the steam entering the turbine and exiting the turbine. Studies have shown that voltage output decreases when the inlet temperature is above  $\sim 10^{\circ}\text{C}$ , and in this study, we adopted the more conservative assumption of  $22^{\circ}\text{C}$  following the work of Miara and Vörösmarty<sup>22</sup>. For once-through cooling systems, the cooling water inlet temperature is the stream water temperature at inlet of power plant. Alternatively, for recirculating cooling systems, it equals to the sum of wet-bulb temperature at the power plant location and the approach (the difference between the cold water temperature and entering wet bulb temperatures).

Water availability: In order to remove excess heat load, cooling water is extracted from surface streams where the withdrawal rate of cooling water is constrained by available streamflow and maximum withdrawal rate of the pipe. Only the latter is provided by EIA-860. The former is assumed equal to streamflow minus environmental flow. Environmental flow is determined by the Tennant Method following the fair or degrading guideline (Supplementary Table A-1); i.e., 10% and 30% of the long-term monthly streamflow is maintained as an

environmental flow requirement in the month of October-March and April-September, respectively.

Environmental regulations: Power plants also need to comply with environmental regulations, which may result in a forced reduction in heat load when the outlet water temperature approaches the regulated threshold. State-level regulations on maximum temperature in fresh water streams (°C), maximum temperature rise of fresh water streams from ambient water temperature (°C), and thermal variance (°C) are presented and discussed in Supplemental Section 4. For recirculating systems, the discharged water flow is much less compared to the intake water withdrawal water via evaporation into the atmosphere (a.k.a., latent heat transfer). Therefore, regulations on maximum stream temperature and temperature rise due to anthropogenic activities do not apply to recirculating systems in this study.

### 3.2.1 Once-through Cooling System

For once-through systems, usable capacity,  $E$ , is computed as

$$E = \frac{C_p m_{adj} \Delta T_{adj} \eta_{adj}}{\alpha(1 - \eta_{adj} - q_{hs})}$$

where  $C_p$  is the specific heat content of water (4.179 MJ/m<sup>3</sup>K),  $m_{adj}$  is adjusted cooling water withdrawal rate in m<sup>3</sup>/s,  $\Delta T_{adj}$  is adjusted temperature difference between the discharge and intake water temperatures in °C,  $\eta_{adj}$  is the adjusted generation efficiency, and  $q_{hs}$  is the ratio of heat dissipated into sinks other than water.  $q_{hs}$  are assumed constant for steam engine power plants (0.12) and combined cycle power plants (0.2) <sup>128</sup>.  $\alpha$  is the capacity factor, which is different by power plant

and month.  $\eta_{\text{adj}}$ ,  $m_{\text{adj}}$  and  $\Delta T_{\text{adj}}$  vary by climate, streamflow, and environmental policy.

$$\eta_{\text{adj}} = \eta_{\text{opt}} - \eta_{\text{loss}}$$

where  $\eta_{\text{opt}}$  is optimal efficiency and  $\eta_{\text{loss}}$  is the loss of efficiency due to above-optimal inlet temperatures.  $\eta_{\text{loss}}$  is estimated as

$$\eta_{\text{loss}} = \chi_1(T_{\text{ri}} - T_A)^2 + \chi_2(T_{\text{ri}} - T_A)$$

where  $\chi_1$  and  $\chi_2$  are constants.  $T_{\text{ri}}$  is inlet temperature, in this case, the intake water temperature.  $T_A$  is a intake water temperature threshold above which generation efficiency will be reduced. It is assumed to be 22°C.

$m_{\text{adj}}$  is adjusted based on available streamflow  $M_a$  and state-level environmental regulation on allowable outlet water temperature in the mixing zone<sup>22</sup>.  $M_a$  is the maximum available water for use in cooling and is computed as the natural streamflow minus the environmental flow.

CLM-MOSART provides streamflow and water temperature data  $T_{\text{ri}}$  at a daily resolution for the historical period of 2010-2012 and future period of 2013-2099 under RCP4.5 and RCP8.5 scenarios.

The allowable temperature adjustment,  $\Delta T_{\text{adj}}$  is dictated by state-level environmental regulation of allowable outlet water temperature in the mixing zone and maximum allowable temperature rise in the stream (Supplementary Table A-2). More details for computing  $\eta_{\text{adj}}$ ,  $m_{\text{adj}}$  and  $\Delta T_{\text{adj}}$  are found in Miara and Vörösmarty

<sup>22</sup>.

### 3.2.2 Recirculating Cooling System

For recirculating systems, the usable capacity,  $E$ , is computed as

$$E = \frac{Q_{\text{adj}} \eta_{\text{adj}}}{\alpha}$$

where  $Q_{\text{adj}}$  is adjusted heat input (MJ), which is constrained by available streamflow,  $M_a$ , in conjunction with the following conditional check.

$$\text{If } m_{\text{mu}} < M_a, Q_{\text{adj}} = Q_{\text{in}}$$

$$\text{Otherwise, } Q_{\text{adj}} = \frac{M_a}{m_{\text{mu}}} \times Q_{\text{in}}$$

where  $m_{\text{mu}}$  is the make-up water required by the cooling tower ( $\text{m}^3/\text{s}$ ) and  $Q_{\text{in}}$  is the heat input. Both variables are reported by EIA-923.

$\eta_{\text{adj}}$  is computed following the same approach as for once-through systems, except that inlet temperature  $T_{\text{ri}}$ , in this case, equals to the wet-bulb temperature  $T_{\text{wb}}$  plus approach A ( $^{\circ}\text{C}$ ). We followed the same assumption for A as in Miara and Vorosmarty (2013), and  $T_{\text{wb}}$  is estimated using air temperature  $T$  (K) and relative humidity RH% specified at the boundaries<sup>129</sup>. Surface pressure  $P$  (Pa) at monthly time step and specific humidity  $q$  (kg/kg) at daily times step were provided by NLDAS2 climate forcing to compute the wet-bulb temperature for each recirculating power plant follow the following steps.

First, the saturated vapor pressure  $e_{\text{sat}}$  (Pa) is computed using the Clausius-Clapeyron equation,

$$e_{\text{sat}} = e_{s0} \exp \left( \frac{L_v}{R_v} \left( \frac{1}{T_0} - \frac{1}{T} \right) \right)$$

where  $e_{s0}$  equals to 611Pa,  $L_v$  equals to  $2.5 \times 10^6 \frac{J}{kg}$ ,  $R_v$  is  $461.5 \frac{J}{kgK}$ , and  $T_0$  is 273.15K. Next, the specific humidity at saturation,  $q_{sat}$ , is computed with the near surface approximation as

$$q_{sat} = \frac{\varepsilon}{p} e_{sat}$$

where  $\varepsilon$  is a constant of 0.622. Hence, the relative humidity, RH%, is now computed as

$$RH\% = \frac{q}{q_{sat}} \times 100\%$$

Finally, the wet-bulb temperature  $T_{wb}$  is approximated based on Stull<sup>130</sup> as

$$\begin{aligned} T_{wb} = T \tan \left[ 0.151977(RH\% + 8.313659)^{\frac{1}{2}} \right] + \tan(T + RH\%) \\ - \tan(RH\% - 1.676331) \\ + 0.00391838(RH\%)^{\frac{3}{2}} \tan(0.023101RH\%) - 4.686035 \end{aligned}$$

## Supplementary Notes

### Supplementary Note 1. Environmental Regulations

Environmental regulations on water temperature variations were compiled from a 1988 Environmental Protection Agency (EPA) document on state and federal water quality standards<sup>131</sup>. Supplementary Table 2 includes the summary of water temperature criteria for each of the 50 states. Note that standards are set for three distinct variables: 1) maximum temperature in fresh water streams (°C), 2) maximum temperature rise of fresh water streams from ambient water temperature (°C), and 3) thermal variance (°C) defined as exceedance allowed beyond a maximum

temperature. Standards on the three variables vary from state to state, but in general, maximum temperature and maximum temperature rise varies around 32°C and 2.8°C, respectively. A majority of states do not have explicit standards on thermal variance. In addition, many states set standards according to the classification of water type (e.g., fresh vs. saline, river vs. lake, surface vs. ground, inland vs. coastal), purpose of water (e.g., drinking, recreation, agriculture, industry, navigation) and water quality (e.g., warm biota vs. cold biota). Further, some states employ geographically and seasonally heterogeneous standards for water bodies within its jurisdiction. Due to the complex characterization of the state standards, we adopted the following criteria in order to specify a single numeric value for each state (narratives used in the regulation are in italic form).

- Choose values for *inland water bodies* where it applies
- Choose values for *freshwater streams* where it applies
- Choose values for *water for industry* where it applies
- Choose values for *surface water* where it applies
- Choose the *maximum value* for the state if standards are geographically and seasonally heterogeneous
- Choose values for *warm biota water* where it applies
- Assume 32°C for maximum temperature, 2.8°C for maximum temperature rise, and 0°C for thermal variance in the handful of states where no numerical standards are found.
- Select the highest value under each criterion if none of the above criteria apply.



## Supplementary Note 2. Model Validation

The TPGM model was simulated at daily time step and subsequently compared against reported thermoelectric power production values for the historical period of 2010-2012. Five simulations for once-through systems whereas four simulations for recirculating systems were conducted as shown in Supplementary Table A-3.

Supplementary Figure A-4 (a) displays the monthly power production aggregated from daily simulations over the entire once-through sample. The three levels of constraints have significant impacts during summer months (June to August) when temperatures are greatest and streamflow is limited. During this high electricity demand season, actual power productions are generally 10%-20% lower than when operating under “optimal” conditions. When accounting for efficiency loss due to inlet ambient temperature, the results are lower in terms of electrical output relative to optimal conditions. Constraints bindings from streamflow availability and the Clean Water Act 316(a) further bring our simulation closer to reported values (mean bias% is 8.2% for the blue line, 4.3% for the green line, and 2% for the bold red line, respectively). Similar behaviors are also observed for recirculating systems (Supplementary Figure A-5 (b)). Incorporating these three constraints into the modeling framework brings the simulation closer to observations (mean bias is 5.6% for the blue line and 2% for the bold green line).

Note that for once-through systems, shutting down power plants (without waivers) leads to a 20%-45% loss of summer capacity compared to continued

operation (with waivers). For recirculating systems, supply loss in summer is 10%-20% if waivers are not granted.

Supplementary Figure A-5 display the relative differences between simulated annual power production and reported annual power production aggregated over the historical period from 2010-2012 at the power plant level. The majority of the power plants show biases between -20% and 20%, which are considered good agreement with reported values.

#### Supplementary Note 3. Limitations and Implications

Because RCP4.5 prognosticates a world in which climate change mitigation policies transform our current energy system from fossil fuel dominant to a mixture of renewable and non-renewable energy <sup>42</sup>, climate impacts on thermoelectric generating capacity will likely be less severe than what this study implies owing to several reasons: 1) new thermal capacities that are proposed to be built will utilize technologies with lower water requirements and lower carbon emissions <sup>132</sup>. For example, dry cooling and recirculating cooling tower technologies will supersede traditional, once-through cooling technologies. Similarly, combustion turbines and combined cycle generation technologies will replace traditional steam engines <sup>133</sup> suggesting enhanced adaption of new capacities to external environmental changes. 2) Further, even more efficient thermoelectric power plants are emerging <sup>132</sup> that will help to mitigate reductions in overall cooling water requirements, and thus, help alleviate usable capacity losses.

Finally, due to different interpretations of guidelines on discharge effluents by each state, we assumed a uniform value for each state following a set of clear criteria.

The interpretation of the criteria includes some objectivity, but they serve well to screen out a meaningful interpretation of the regulation for the water body of interest. This is an improvement on the existing literature that does not acknowledge regional heterogeneity nor model the full interpretation of the regulation (a.k.a., maximum temperature in fresh water streams, maximum temperature rise of fresh water streams from ambient water temperature and thermal variance). Future work may include a full assessment across a range of regulatory schemes that highlight the stringency of regulatory enforcement as well as heterogeneity in waiver frequency across jurisdictions.

## Appendix B

### Supplementary Figures

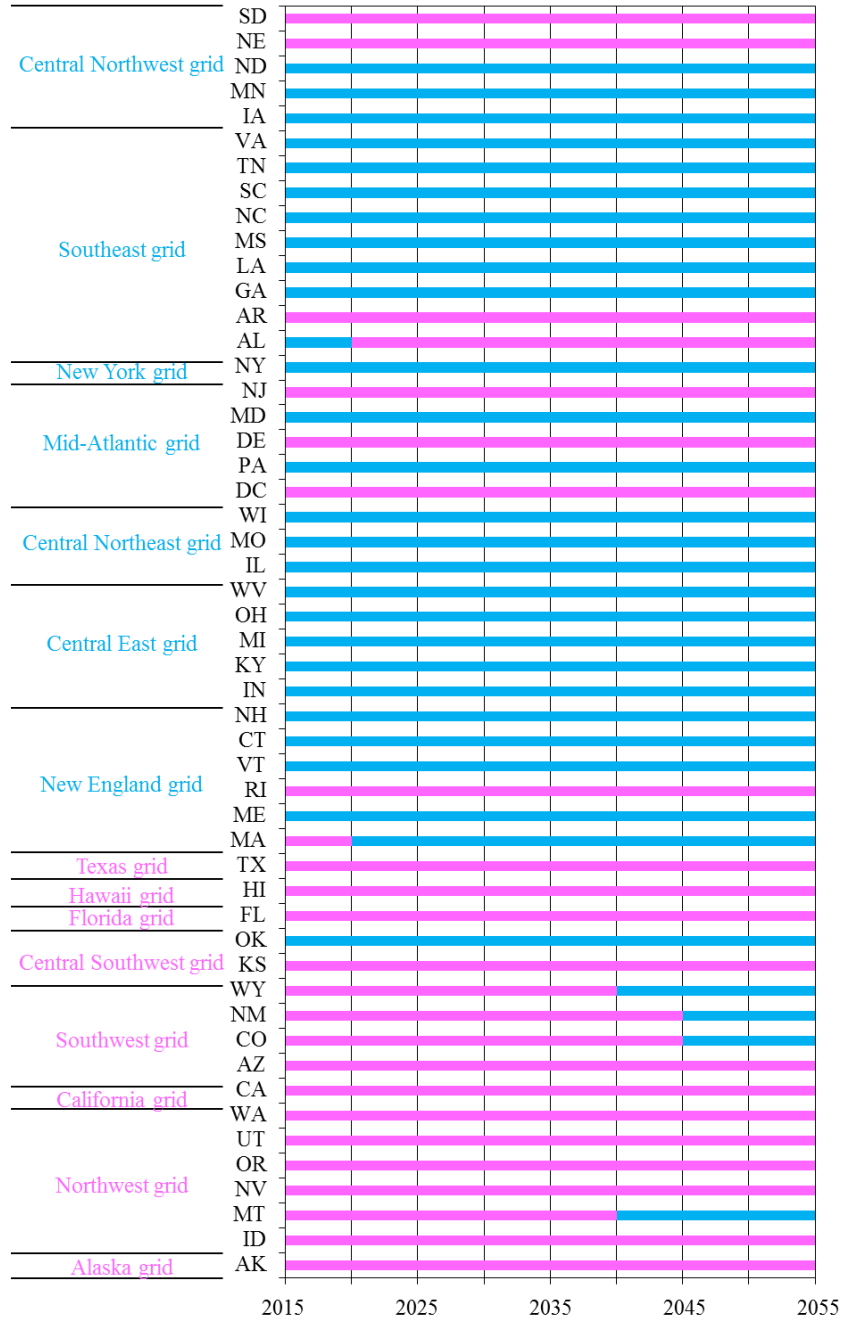


Figure B-1 Indication of water binding effect for future period (pink is binding and blue is non-binding)

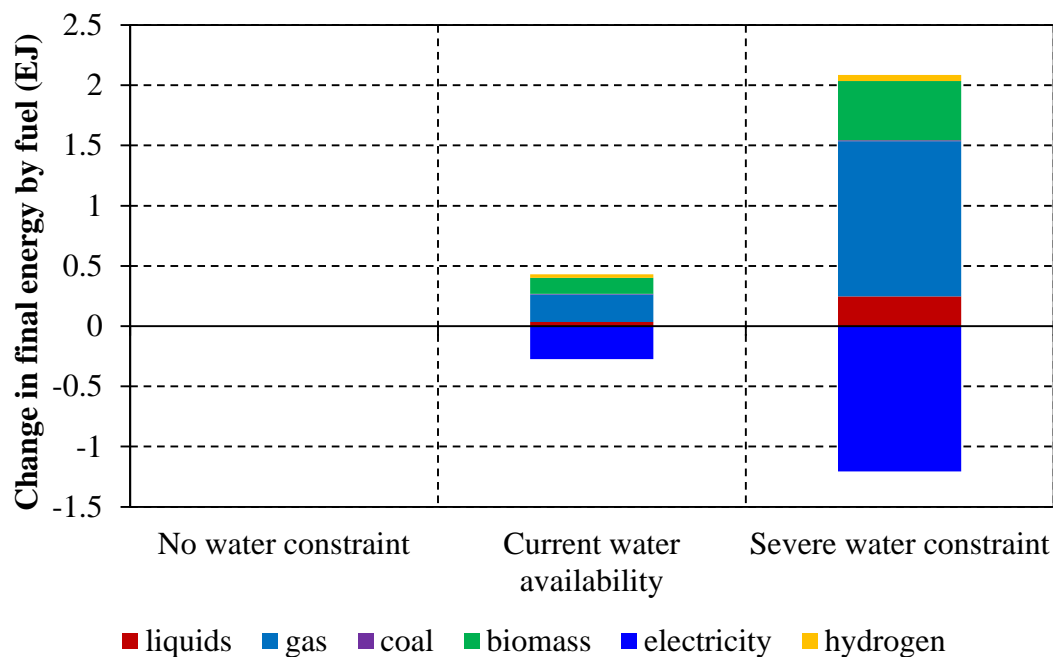


Figure B-2 Final energy by fuel in 2050 relative to the no water constraint scenario

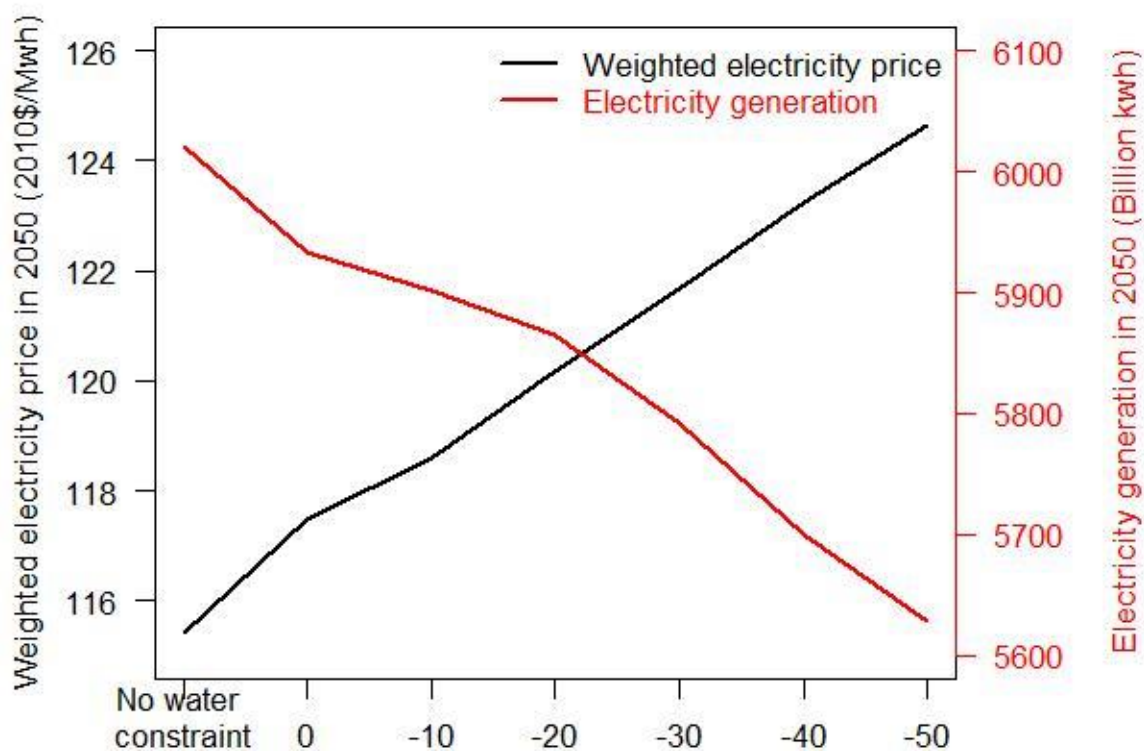


Figure B-3 Total U.S. electricity generation and unit price as a function of increasing water constraints (the numbers indicate % of current water availability, for example, -50 indicated 50% of current water availability, e.g. severe water constraint scenario)

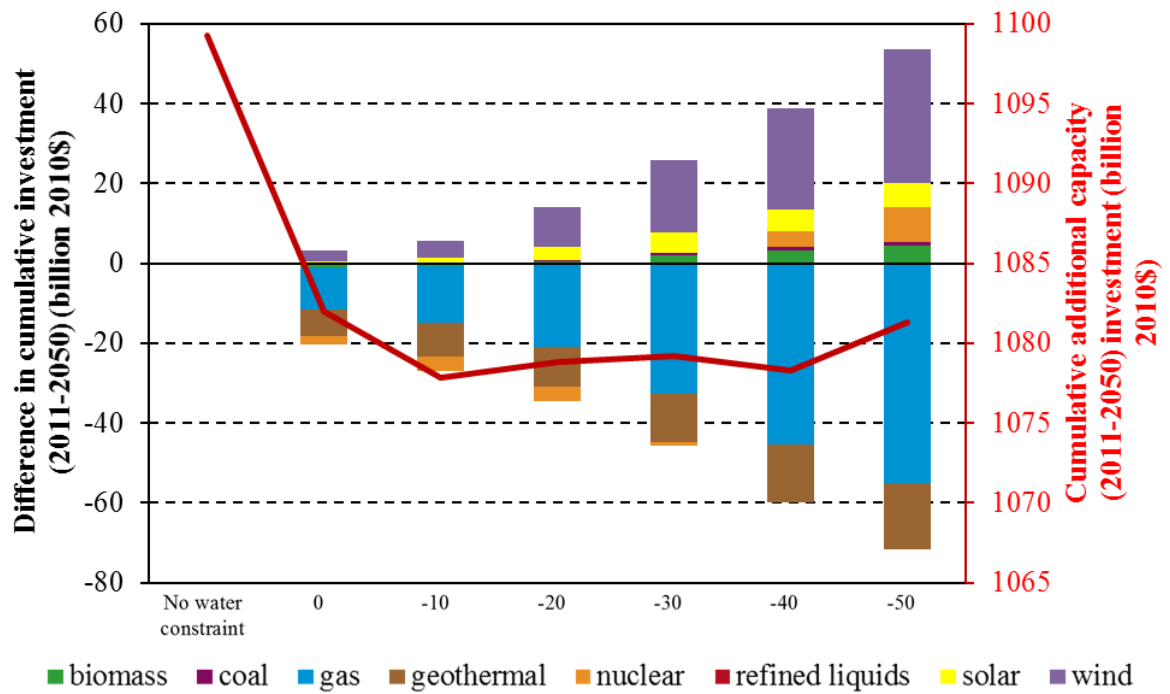
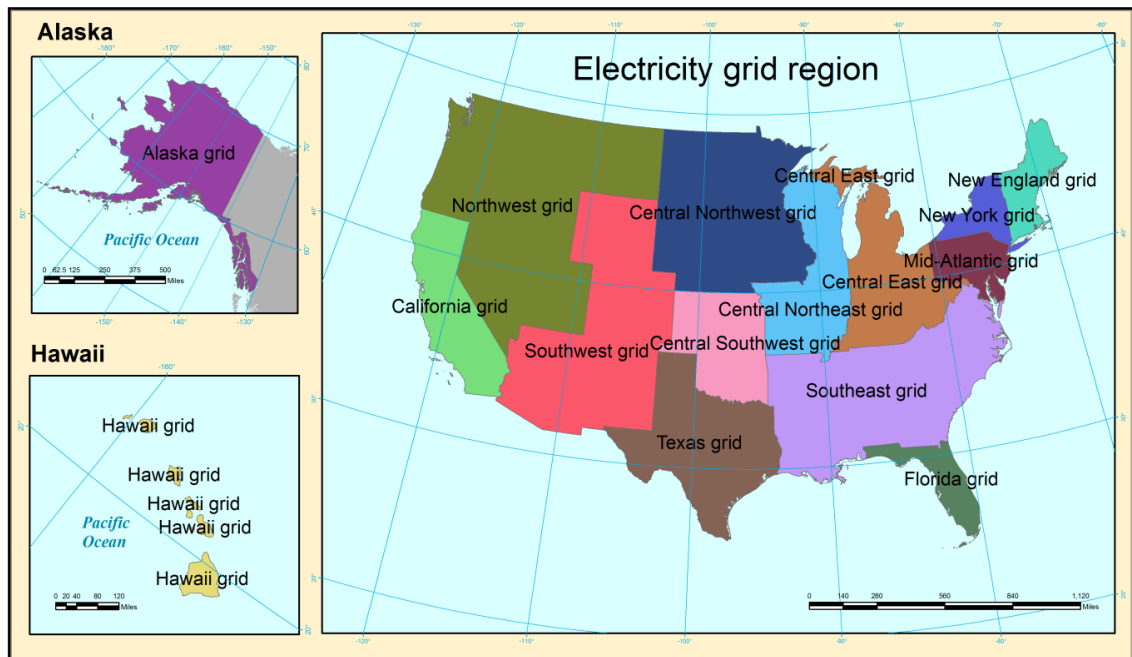
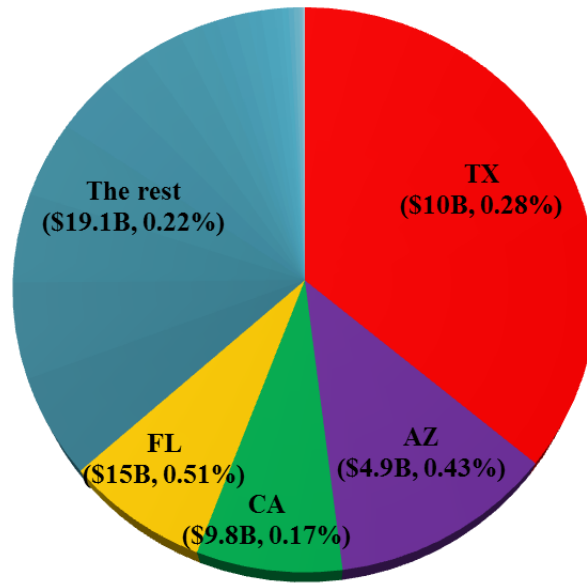


Figure B-4 Change in cumulative investment in new generating capacities across the U.S. as a function of increasing water constraints



*Figure B-5 Electricity grid region defined in this study. These groups of states are defined to closely match the North American Electric Reliability Corporation (NERC) region.*



*Figure B-6 Share of forced-retired capacity by state compared to total forced retired capacity across the country, including the cost of meeting the severe water constraint by 2050 (in parentheses, billion 2010\$, % of GDP).*

#### Supplementary Tables

Table B-1 Inter-comparison between similar studies investigating water availability and U.S. electrical generation

	<b>This study</b>	<b>Macknick et al. (2015)</b>	<b>Tidwell et al. (2016)</b>	<b>Webster et al. (2013)</b>
Spatial scale and model year	US 2010-2050	US 2010-2050	Western US 2013-2032	The state of Texas 2050
Model	GCAM-USA-water	ReEDS	PCM and LTPT	Mixed Integer Linear Programming
Treatment of water constraints	Incremental decrease of water availability	Water access availability and cost by water source	Compare calculated water consumption	50% reduction in water withdrawal



	with respect to current water availability appropriated to the electricity sector (combination of Tidwell et al., 2017 and USGS, 2010)	(Tidwell et al., 2014)	with water availability	relative to the no-limit case
Scenarios	No limits  Current water availability  10 – 50% reduction from current water availability	Different combinations of restrictions on water access and once-through cooling technology	Diversified electricity supply scenarios	No limits  75% CO <sub>2</sub> reduction  75% CO <sub>2</sub> reduction and 50% H <sub>2</sub> O reduction
Treatment of electricity demand	Projection of electricity demand	Exogenously assumed fixed demand	Exogenously assumed fixed demand	Exogenously assumed fixed demand
Cooling technology mix	Assumed fixed share (based on UCS)	Modeled based on cost	Assumed all future builds use closed-loop cooling.	Modeled based on cost
Key observations	Water constraints have significant impact on both national and regional scale in terms of investment and trade. Impacts vary substantially	Current water policy and prices have little impact on the national trend in the electricity sector and national greenhouse gas emission. However, there	Very few hubs hit the water limit.  Results could have change substantially if scenarios favoring higher-intensity water use technology had been	Simultaneous restriction of CO <sub>2</sub> emissions and water withdrawals requires a different mix of energy technologies and higher costs than one

	from state to state and there is an evident regional pattern.	are regional implications.	explored.	would plan to reduce either CO2 or water alone.
Advantages	<p>Models trade dynamics to some extent</p> <p>Implemented national and subnational energy policy</p> <p>Models energy demand based on a number of factors</p> <p>More realistic water constraints</p>	<p>Resolved at Balancing Area (BA) level</p> <p>Optimizes capacity and transmission investment</p>	Resolved at transmission planning hub level	<p>Incorporated load-duration curve for energy demand</p> <p>Uncertainty analyses of future fuel cost and technology cost</p>

Table B-2 Initial input data used to define the water constraint scenarios

East US	GCAM 2010 electricity water withdrawal (km <sup>3</sup> /year)	Untapped water (km <sup>3</sup> /year) <sup>63</sup>	Fraction of electricity water withdrawal <sup>2</sup>	Available water supply for the electricity sector (km <sup>3</sup> /year)
AL	12.23	208.50	0.83	184.93
AR	1.07	0.21	0.14	1.10
CT	0.21	4.07	0.24	1.20
DE	0.30	0.08	0.03	0.30
FL	5.21	8.31	0.10	6.03
GA	4.68	50.31	0.40	24.73
IA	4.11	147.41	0.73	111.66
IL	14.86	614.36	0.82	516.66
IN	9.93	198.30	0.62	133.40
KY	4.58	743.36	0.78	581.42
LA	5.03	748.73	0.52	393.43

MA	1.86	3.61	0.13	2.32
MD	3.04	9.20	0.30	5.76
ME	0.22	4.92	0.07	0.54
MI	13.44	44.73	0.79	48.73
MN	4.08	70.94	0.66	50.69
MO	11.38	669.14	0.69	472.83
MS	2.22	376.00	0.25	95.59
NC	14.31	43.32	0.69	44.21
NH	0.67	18.17	0.55	10.67
NJ	2.81	0.13	0.27	2.84
NY	8.62	58.97	0.48	37.03
OH	12.63	208.88	0.76	172.39
PA	10.04	81.60	0.66	64.14
RI	0.05	0.02	0.01	0.05
SC	10.29	51.93	0.81	52.42
TN	7.36	362.47	0.75	280.39
VA	9.44	45.21	0.64	38.56
VT	0.96	36.96	0.80	30.54
WI	7.27	79.80	0.75	67.24
WV	3.19	124.17	0.70	90.07
<b>West US</b>				
ND	1.52	13.80	0.74	11.75
SD	0.19	0.03	0.02	0.19
MT	0.35	0.55	0.02	0.36
WY	0.69	0.17	0.01	0.69
NE	5.59	10.70	0.22	7.97
CO	0.42	0.02	0.01	0.42
KS	1.59	0.11	0.09	1.60
NM	0.83	0.00	0.02	0.83
OK	0.65	15.83	0.22	4.09
TX	11.04	1.55	0.46	11.75
UT	0.15	0.00	0.02	0.15
AZ	0.51	0.00	0.02	0.51
NV	0.14	0.00	0.01	0.14
CA	0.81	0.06	0.00	0.81
ID	0.00	0.00	0.00	0.00
OR	0.23	0.05	0.00	0.23
WA	0.05	0.00	0.01	0.05
<b>Other s</b>				
AK	0.05	0.00	0.07	0.05
DC	0.00	0.00	0.00	0.00
HI	0.01	0.00	0.08	0.01

## Supplementary Notes

### Supplementary Note 1. Comparison with other studies

Webster et al.<sup>134</sup>, Macknick et al.<sup>27</sup> and Tidwell et al.<sup>28</sup> do not fully capture the interactions of the electricity system with other sectors of the economy including energy demand. In contrast, our study takes an integrated perspective. Our study fills these gaps by employing a state-level model of the U.S. energy system with detailed representations of the supply and demand of electricity for all of the 50 states including the District of Columbia. In addition, our model accounts for the interaction of the electricity sector with other sectors in the broader economy. Finally, as we explain below and in the SI, our representation of water constraints accounts for water appropriation to all demanding sectors (Supplementary Table B-1).

As water resources are shared by end users other than just electricity generators, water availability in the natural system, and its allocation to end users, can result in different levels of water stress faced by the electricity sector depending on location in the U.S. Water rights and allocation doctrines in the U.S. are complex at the state level, but in general, the western U.S. follows the doctrine of prior-appropriation water rights to allocate their use of water, while the eastern U.S. applies riparian water rights. Some states adopted a mixed system. There are also specifications of water rights for surface water and groundwater at the state level<sup>135</sup>. The different water resource abundance and allocation practices between western and eastern U.S. may lead to very different adaptation strategies in electricity capacity expansion across regions. Webster et al.<sup>134</sup> focused on one state in the West and

configured water constraints in a hypothetical approach. Both Macknick et al.<sup>27</sup> and Tidwell et al.<sup>28</sup> considered water allocation practiced in the U.S., but overestimated water availability by assuming all water resources are readily available for use by the electricity sector. This results in biased output and can underestimate the impacts of water constraints on the energy system. In addition, end-user electricity demand is exogenously assumed in all of these studies, and thus, electricity supply-demand dynamics are not well captured or reflected in electricity capacity expansion.

#### Supplementary Note 2. Computation of trade fraction

Definition of trade fraction is two-fold. For net exporter, it is the fraction of electricity generated within state being exported. For net importers, it is the fraction of electricity consumed within state being imported. In mathematical notation, it can be shown as:

$$Trade\ fraction = \begin{cases} \frac{Trade}{Generation} & Net\ exporter \\ \frac{Trade}{Generation + Trade} & Net\ importer \end{cases}$$

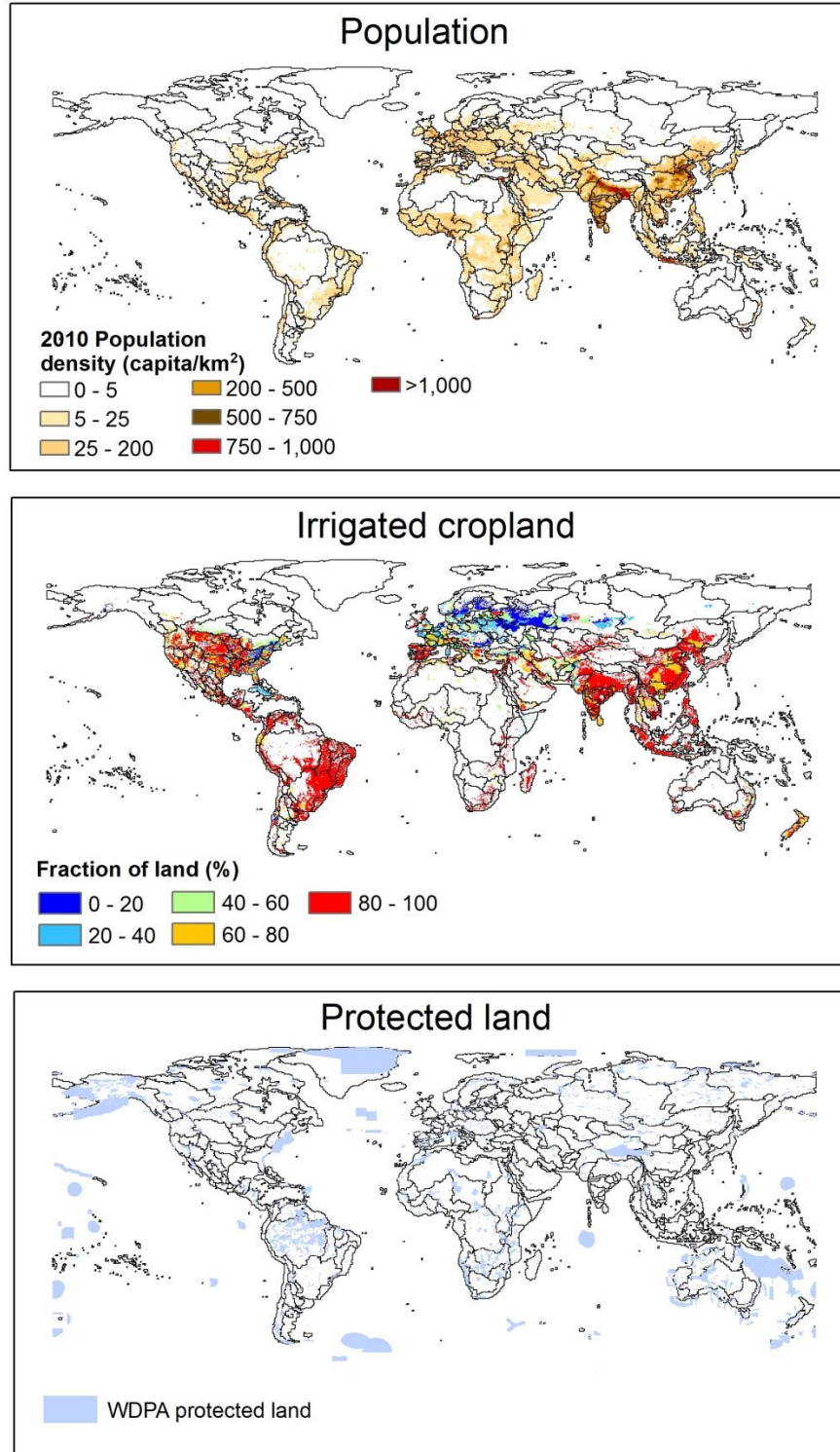
Therefore, change of trade fraction is computed as:

$$\Delta Trade\ fraction = \begin{cases} \frac{Trade_2}{Gen_2} - \frac{Trade_1}{Gen_1} & Net\ exporter \\ \frac{Trade_2}{Gen_2 + Trade_2} - \frac{Trade_1}{Gen_1 + Trade_1} & Net\ importer \end{cases}$$

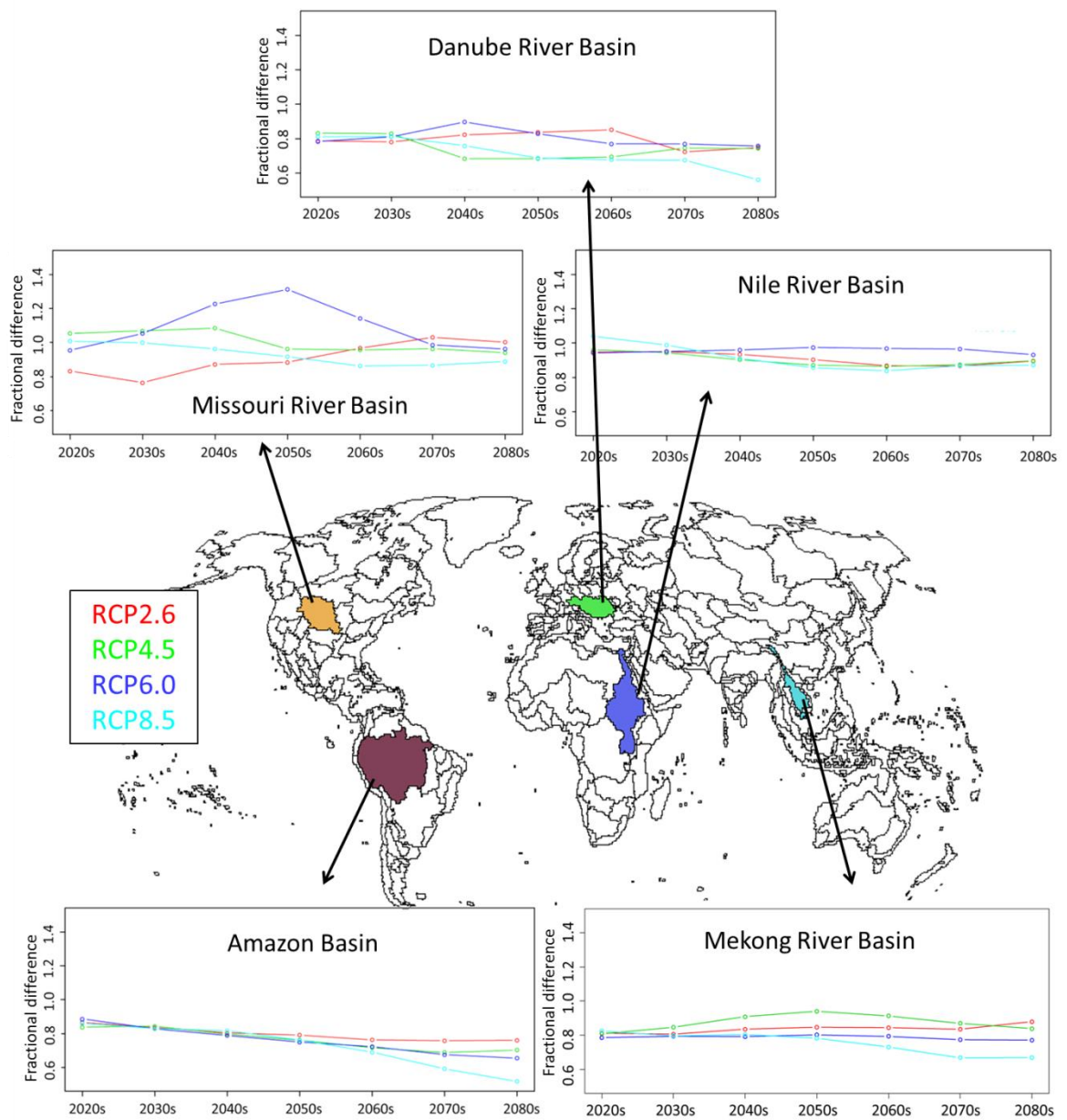
where 1 and 2 indicate different water constraint scenarios.

## **Appendix C**

### Supplementary Figures



*Figure C-1 Exclusion zones defined for this study: population (SSP1 projection in 2010 as demonstration), irrigated area, and protected land.*



*Figure C-2 Impacts of climate change on reservoir inflow for selected basins and RCPs. Y-axis values show the fractional difference between the future inflows and the historical inflows.*



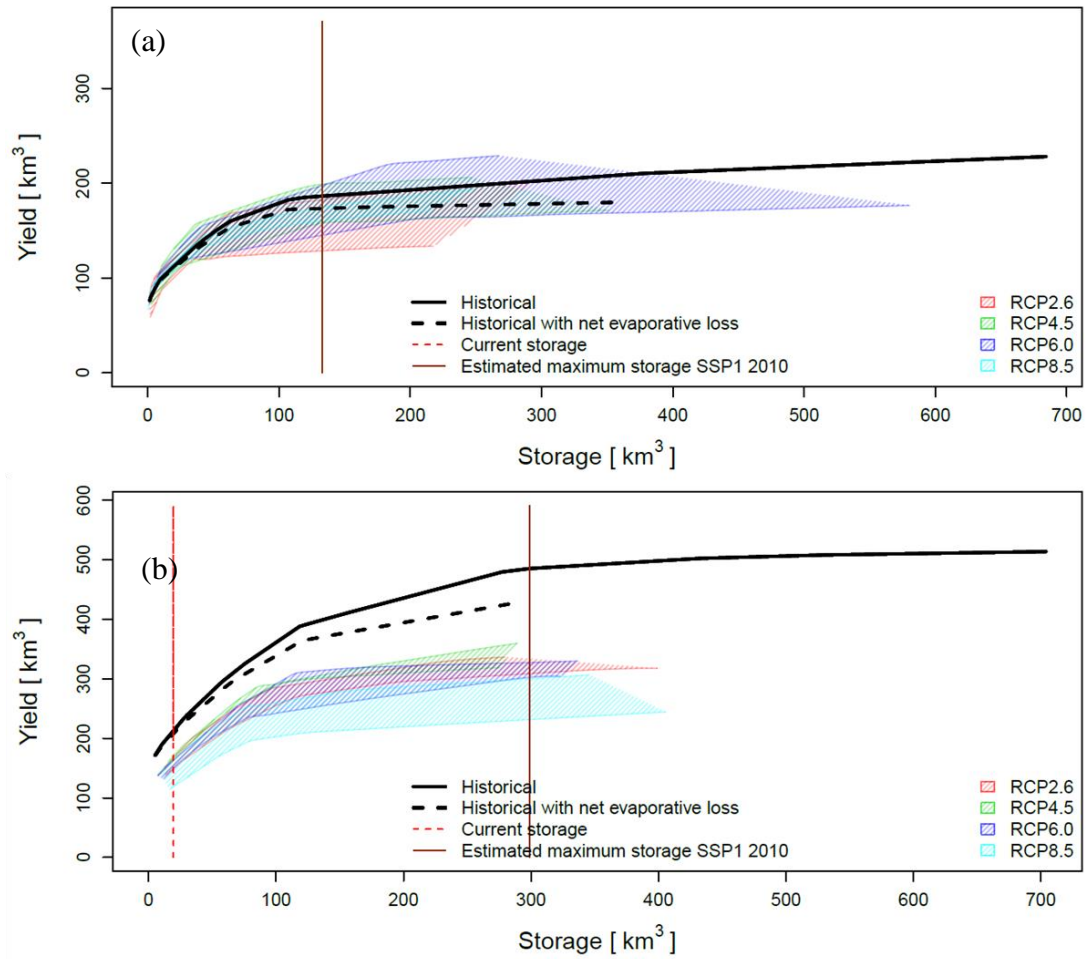
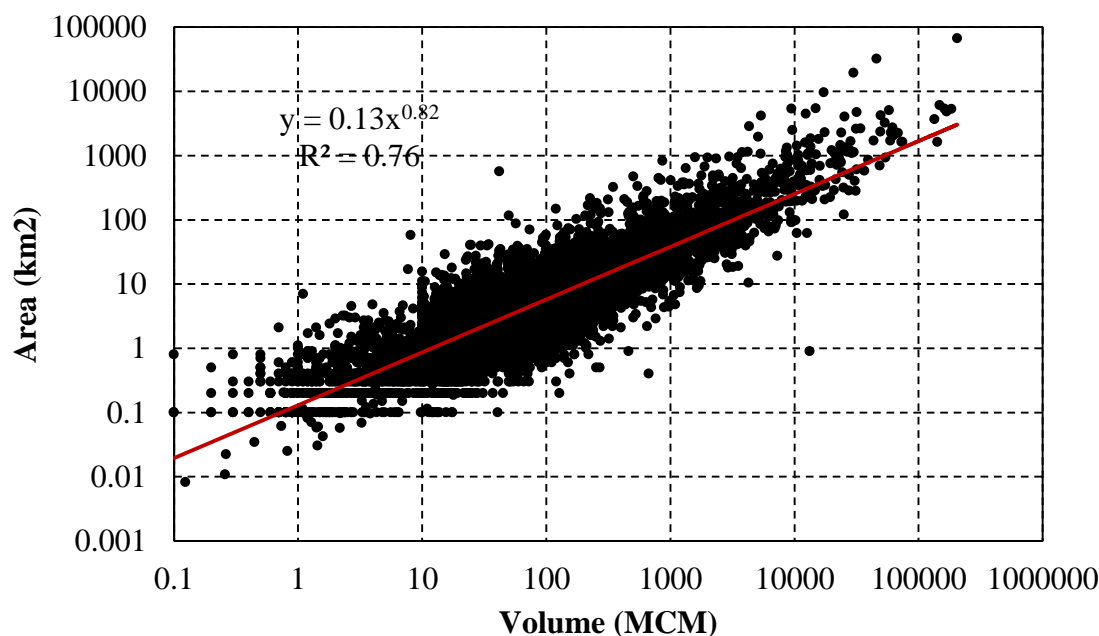


Figure C-3 S-Y curve for (a) Missouri River Basin, North America (b) Mekong River Basin, Southeast Asia



*Figure C-4 Surface area-volume relationship (log scale) derived from GRand reservoir database for all existing reservoirs.*

## Supplementary Tables

Table C-1 Summary of data that defines the exclusion zones

Exclusion zones	Source	Data versions	Unit	Resolution	Varies over time?
Population	Jones and O'Neill, 2016	SSP1, SSP2, SSP3, SSP4, SSP5	Number of people	0.125 degree	Yes
Cropland	Siebert et al., 2013	Irrigated and rain-fed	Percentage of area per grid cell	0.0833 degree	Static
Protected area	Deguignet et al., 2014	World Database on Protected Areas (WDPA)	Locations of protected area (land and marine)	Polygons	Static

## Supplementary Methods

## 1. Simplified area-volume relationship for reservoirs

A nonlinear area ( $A$ )-volume ( $V$ ) relationship is identified in the form of

$$V = cA^b \quad (\text{C.1})$$

where  $c$  and  $b$  are basin-specific parameters. The area-volume relationship is derived from GRanD data of existing reservoirs within each basin. In basins where no reservoirs currently exist, a uniform relationship is derived from all reservoirs globally (Figure C-4).  $c_{max}$  in equation 3g is therefore calculated for each basin by plugging in estimated total available land area as discussed in section 4.2.3.

Based on GRanD data for existing reservoirs, we further provided an estimate of the  $a$  variable in section 4.2.2 equation (4.2). We simply took the ratio of the sum of surface area and the sum of maximum storage capacity for all existing reservoirs within each basin, and assume this ratio to be the surface area per unit storage volume ( $a$ ) for each representative reservoir.

The area-volume relationships extrapolated from the GRanD database reflect some level of topographic features of the region but lack explicit characterization of the terrain at sufficient resolutions needed to site specific locations for new reservoirs. However, the basin-averaged relationships capture the main topographic variations across regions, and given the global scale of this study, this simplification is considered an acceptable first-order approximation.

## 2. Net surface flux calculation

Storing water in reservoirs increases the surface area of the waterbody, which results in increased evaporation. Net evaporative losses from the reservoir surface were computed on a 0.5-degree global grid for each RCP scenario. First, the

evaporation (mm/day) from the aggregated reservoir surface is estimated using the method developed by Shuttleworth<sup>98</sup> as

$$e_e = \frac{mR_n + \gamma \times 6.43 \times (1 + 0.536 \times U_s)\delta_e}{\lambda_v(m + \gamma)} \quad (C.2)$$

where  $e_e$  is the estimated evaporation in  $\text{mm day}^{-1}$ ,  $U_s$  is the wind speed in  $\text{m s}^{-1}$ , and  $\lambda_v$  is the latent heat of vaporization of water in  $\text{MJ kg}^{-1}$ . The model parameter  $\delta_e$  is the vapor pressure deficit in kPa, and is computed from

$$\delta_e = (1 - RH)e_s \quad (C.3)$$

where RH is relative humidity in % and  $e_s$  is saturated vapor pressure in kPa, which can be obtained using the approximation in Merva<sup>136</sup>.  $R_n$  is net irradiance in  $\text{MJ m}^{-2} \text{day}^{-1}$ , which is computed as

$$R_n = (1 - \alpha)R_{SW}^\downarrow + R_{LW}^\downarrow - \varepsilon\sigma T_s^4 \quad (C.4)$$

where  $\alpha$  is the albedo of water (assumed to be 0.1, adopted from Table 8 in Budyko and Milelr<sup>137</sup>),  $R_{SW}^\downarrow$  is downward shortwave radiation and  $R_{LW}^\downarrow$  is downward longwave radiation in  $\text{MJ m}^{-2} \text{day}^{-1}$ .  $\varepsilon$  is the broad band emissivity of water (assumed to be 0.96 as a mid-value in the cited range ([http://www.engineeringtoolbox.com/emissivity-coefficients-d\\_447.html](http://www.engineeringtoolbox.com/emissivity-coefficients-d_447.html))),  $\sigma$  is the Stephan-Boltzmann constant ( $5.67 \times 10^{-8} \text{ kg s}^{-3} \text{ K}^{-4}$ ), and  $T_s$  is the surface temperature of water in K. The psychrometric constant  $\gamma$  in  $\text{kPa K}^{-1}$  is estimated as

$$\gamma = \frac{0.0016286P}{\lambda_v} \quad (C.5)$$

where  $P$  is surface atmospheric pressure in kPa. The last variable  $m$  is defined as the slope of the saturation vapor pressure curve in  $\text{kPa K}^{-1}$ , which is estimated following ASAE<sup>138</sup> as

$$m = \frac{de_s}{dT_a} = 0.04145e^{0.06088(T_a - 273.15)} \quad (\text{C.6})$$

where  $T_a$  is the surface air temperature in K. Net surface flux  $e$  (mm/day) is therefore the difference between estimated evaporation  $e_e$  and precipitation  $p$  (mm/day).

$$e = e_e - p \quad (\text{C.7})$$

Basin-specific total net surface flux in volumetric units ( $\text{m}^3$ ) is obtained by multiplying the basin averaged net surface flux rate by total aggregated reservoir surface area ( $A_t$  in section 4.2.2 equation (4.2)) within each basin.

### 3. Exclusion zones

Table C-1 lists important characteristics of the datasets used to define the three exclusion zones in this study.

Protected land and cropland area are held constant over the simulation horizon due to a lack of suitable projections aligned with the SSP scenarios. It is important to note that future expansion of cropland is anticipated and could further restrict reservoir expansion. Developing specific rules and policies reflecting siting decisions, as well as policies addressing future protected areas, is beyond the scope of this current study. Grid cells occupied by urban population, existing cropland, or designated as a protected area are considered as exclusion zones. Historical reservoir development suggests that areas occupied by rural population are considered potential available lands for reservoir expansion<sup>71,108</sup>. There is significant controversy surrounding the ethics of flooding upstream populated areas for reservoir

development, and as engineering scientists we decided to approach this issue by defining a range of rural population density cutoff values above which grid-cells are considered unfit for reservoir expansion. Essentially, a cutoff value of rural population density equal to 0 capita per km<sup>2</sup> suggests that all rural areas are considered un-exploitable for reservoir expansion; a cutoff value of 1244 capita per km<sup>2</sup>, which is obtained from the number of rural residents relocated for building the Three Gorges Dam<sup>139</sup>, is assumed in this study to be a maximum limit for relocation of rural populations due to reservoir inundation. A higher threshold suggests more land for reservoirs and less land to be retained for rural population.

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