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EDITORIAL

Vulnerabilities and opportunities at the nexus of electricity, water and climate

Peter C Frumhoff[1], Virginia Burkett[2], Robert B Jackson[3], Robin Newmark[4], Jonathan Overpeck[5] and Michael Webber[6]

[1] Union of Concerned Scientists, Cambridge MA, 02138 USA
[2] United States Geological Survey, Reston VA 20192 USA
[3] School of Earth, Energy, and Environmental Sciences, Stanford University, Stanford CA 94305 USA
[4] National Renewable Energy Laboratory, Golden, CO 80401 USA
[5] Institute of the Environment, University of Arizona, Tucson, AZ 85721 USA
[6] University of Texas at Austin, Austin TX 78712 USA

E-mail: pfrumhoff@ucsusa.org

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Abstract

The articles in this special issue examine the critical nexus of electricity, water, and climate, emphasizing connections among resources; the prospect of increasing vulnerabilities of water resources and electricity generation in a changing climate; and the opportunities for research to inform integrated energy and water policy and management measures aimed at reducing vulnerability and increasing resilience. Here, we characterize several major themes emerging from this research and highlight some of the uptake of this work in both scientific and public spheres. Underpinning much of this research is the recognition that water resources are expected to undergo substantial changes based on the global warming that results primarily from fossil energy-based carbon emissions. At the same time, the production of electricity from fossil fuels, nuclear power, and some renewable technologies (biomass, geothermal and concentrating solar power) can be highly water-intensive. Energy choices now and in the near future will have a major impact not just on the global climate, but also on water supplies and the resilience of energy systems that currently depend heavily on them.

1. Introduction

Across the globe, the availability of water and electricity are intimately linked to each other and to climate. Water improves the efficiency of power plants and is important for the production of most fuels. Energy availability improves water quality and helps deliver it to our homes. At larger scales, the availability of affordable, reliable energy can yield an abundance of freshwater, through desalination or inter-basin water transfers. Reciprocally, plentiful water can be converted to an abundance of clean energy, through hydroelectric power and irrigated bioenergy crops.

We increasingly live, however, in a world of resource constraints. Water shortages from drought and high water temperatures can force power plants to curtail electricity production, for example, Drought can also inhibit the growth of bioenergy crops. In turn, energy outages disrupt water systems. These disruptions can pose severe economic, public health and environmental risks.

Climate is an important context for considering vulnerabilities and adaptive capacity at the nexus of electricity and water, as climate variability and change can stress the production and supply of both water and energy. By limiting greenhouse gas emissions, clean energy also avoids worsening the impacts of climate change on water availability and temperature and electricity supply and demand (Chandel *et al* 2011). Climate change is already affecting many aspects of water management, including those related to electricity generation (Jiménez Cisneros *et al* 2014). Moreover, we now have a much better understanding of the full range of natural climate variability, including the fact that decades-long droughts can develop in most, perhaps all, of the world's semi-arid regions (Ault *et al* 2014).

The changes in climate most salient to the nexus of energy and water include increasing temperatures (and hence increased evaporation and potential evapotranspiration along with reduced power plant efficiency), and, for many regions, a reduction in mean precipitation. To a first approximation, many dry regions will get drier, and some wet regions will as well (IPCC 2013). In some regions, the combination of substantial warming, increased evaporation, and enhanced potential evapotranspiration will reduce soil moisture and surface water flow even under conditions of increasing mean annual precipitation (IPCC 2013, Vano *et al* 2014, Cook *et al* 2015).

Climate change is expected to further increase drought frequency and severity, bringing additional stresses to fresh water supplies. In western North America, clear evidence is already emerging of the exacerbating impacts of warming on the severity of drought (Vano *et al* 2014, Griffin and Anchukaitis 2014, Diffenbaugh *et al* 2015). This effect is likely to worsen and become more widespread with continued emissions of greenhouse gases. Moreover, recent work suggests that climate models have substantially underestimated the increasing risk of multi-decadal 'megadroughts' due to climate change (Ault *et al* 2014). If greenhouse gas emissions continue unabated, the probability of such a megadrought impacting the Southwest or Central Plains of the US could exceed 80% by the second half of this century (Cook *et al* 2015).

The net impact of climate change is, increasingly, less water for consumption or energy production in many regions of the globe, especially ones that are water limited today. As temperatures rise and the probability and severity of extreme heat waves increase, demand for electricity will also increase at the same time that less water is available for steam generation and cooling.

This special issue was organized precisely because of the global reach and impact of these and other changes in climate on water resources and energy systems (DOE 2013). It examines the critical nexus of electricity, water, and climate, emphasizing connections among resources and the prospect of increasing vulnerabilities of water resources and electricity generation in a changing climate. It also highlights opportunities for research to inform integrated energy and water policy and management measures that can help reduce these vulnerabilities.

2. Advancing understanding at the electricity, water and climate nexus.

The twenty-two papers in this special issue identify research and data needed to advance understanding of the nexus of electricity, water and climate. All but one (Scott 2013) focus on the water used in power generation, rather than the electricity used in the transport, treatment or heating of water. Many of the papers discuss implications of water use by energy systems for climate change mitigation and adaptation. Several authors describe the data and analytical requirements for improving predictive models and for sensitivity studies that will help broaden the set of policy options available for both the water and energy sectors.

Collectively, the papers in this special issue suggest eight major themes or topics for future work:

(1) *Analyses of the effects of fuel mix and energy systems (*e.g., *pulverized coal versus natural gas combined cycle power plants) on freshwater consumption.* Several regional analyses are presented (e.g. Grubert *et al* 2012); similar analysis for other regions and reflecting on place-specific options could be helpful to decision makers seeking to balance energy and water constraints.

(2) *Improvements in the accuracy of water-use estimates for individual power plants, conducted for the variety of technologies and cooling systems currently in operation along with those expected to be developed and deployed.* These improvements will help reflect how climate change and variability could impact future water use. Recent warm, dry summers in Europe, for example, exposed the vulnerability of the power sector to stresses caused by low water availability for hydropower generation and an increase in cooling water usage for thermoelectric power production (Van Vliet *et al* 2013).

(3) *Methods for estimating water use associated with energy extraction, processing, transportation, and electricity production*. New approaches are needed for an accurate life-cycle assessment of water consumption for power generation and for evaluating policy alternatives. A global analysis (Spang *et al* 2014a) reveals how the composition of national energy portfolios drives the intensity of energy system water consumption. Future research on water consumption for energy production (WCEP) that incorporates higher-resolution data on both energy production and water use will produce a more robust identification of WCEP 'hot spots'—countries with more than 10% of renewable water supply used for energy production. Advances in hot spots to decouple energy systems from vulnerable water supplies could drive technological and policy change with multiple national and regional benefits.

(4) *Improvements in data relevance and quality*. Several articles in this special issue highlight the need for more robust data collection and reporting, while others argue for new metrics that are likely to be needed for decision-making in a warming climate. Meldrum *et al* (2013) conclude that despite extensive collection, screening, and harmonization

efforts for assessing water use impacts, 'estimates for most generation technologies and life cycle stages remain few in number, wide in range, and many are of questionable original quality.' Madden *et al* (2013) conclude that current federal data on thermal discharges from US power plants is 'insufficient to adequately assess their impact on in stream temperatures, or their subsequent effects on aquatic ecosystems and biodiversity.' Averyt and coauthors (Averyt *et al* 2013a) describe inconsistencies in water withdrawal and consumptive use data in the United States and provide insights into how data collection may be enhanced. And Spang *et al* (2014b) conclude that new, consistently applied indicators are needed to empirically assess coupled water–energy systems and to identify hot spots of energy-water vulnerability.

(5) *Improvements in understanding the interconnections between climate mitigation choices and future water resource quality and availability*. Clemmer *et al* (2013) show that water consumption and withdrawal data and models can be used to better understand regional and national impacts on water resources for various scenarios of future electricity supply and inform policy analysis of the design of a water-lean decarbonizing economy. Future research is needed to explore scenarios that involve different technology targets, technology combinations, carbon budgets, or specific energy policy proposals. Sensitivity analyses around specific assumptions, such as electricity demand growth, technology cost and performance, energy prices, and changes in regulatory environments could yield valuable results and help lower costs and environmental impacts.

(6) *Analyses of regional data and trends*. Several papers document how regional trends may differ substantially from national-level results. Some findings are not necessarily intuitive. Scanlon *et al* (2013) show, for example, how power plants in water-scarce Texas are not necessarily more drought vulnerable than those in more humid areas because they are generally pre-adapted to water scarce conditions. Two articles highlight the need to translate electricity modeling results at 'water-relevant' and 'electricity-relevant geographies' (Macknick *et al* 2012b, Sattler *et al* 2012). Using a river-basin based model of surface water rights in Texas, Stillwell and Webber (2013) demonstrate how changes in reservoir storage can affect the response of power plants to drought. The consideration of relevant geographies is important in both the assessment of climate change impacts and the design of adaptation strategies within the power and water sectors.

(7) *Impacts of freshwater use in electricity production on ecosystem services, under current conditions and with a warming climate*. Madden *et al* (2013) assess the impacts of once-through power plant cooling systems on aquatic ecosystems. Pacsi *et al* (2013) examine the viability of using electrical grids to increase water availability in drought-stricken regions by shifting water consumption and withdrawals for power generation to areas with greater water availability. Stewart *et al* (2013) illustrate the consequences of relying on riverine ecosystem services for electricity production in terms of altered freshwater temperatures and flow regimes in the US northeast.

(8) *Contributions to the resolution of regulatory conflicts*. A case study from Mexico (Scott 2013) highlights the need to understand the interconnections of electricity, water and climate issues as a foundation for identifying policy implications and adaptive response options. Miara *et al* (2013) describe how projected temperature change will affect the capacity of streams that are used for cooling water to absorb heat. They identify the need for additional risk assessment to identify the specific regions where conflicts between rising river temperatures and regulatory limits are most likely to occur. Finally, Madden *et al* (2013) discuss the costs of meeting associated regulatory restrictions as a factor in decisions about extending the life of a once-through cooled power plant versus closing or updating its cooling system.

3. Impact of the special issue

The twenty-two papers in this special issue were published between October 2012 and December 2014. Over thirty months, from the first paper's publication through March 2015, these papers were downloaded a total of 77 248 times. This includes a remarkable 14,521 downloads alone for Averyt *et al*'s (2013b) assessment of sectoral contributions to surface water stress in the United States. Six papers published video abstracts which were viewed a total 1458 times. And, despite being of recent vintage, these papers have been subsequently cited 131 times in 21 different journals.

While downloads and citations are one measure of impact within the scientific community, what sets the papers in this special issue apart is their emerging impact on public understanding of this nexus of issues, and on the public policy dialogue.

Bringing new research at the nexus of electricity, water and climate to broader public and policy attention was a core underlying motivation for this special issue. Eleven of the papers[7] were developed under the auspices of the Energy and Water in a Warming World Initiative (EW3), a collaboration among researchers

[7] Averyt *et al* (2013a, 2013b), Macknick *et al* (2012a, 2012b), Sattler *et al* (2012), Clemmer *et al* (2013), Madden *et al* (2013), Flores-Lopez and Yates (2013), Yates *et al* (2013a, 2013b, 2013c).

across disciplines and academic, government and non-profit institutions to co-design policy-relevant research on the water demands of electricity production in the context of climate variability and change. Organized by the Union of Concerned Scientists, EW3 was guided by a scientific advisory committee that included several of this special issue's editors (Frumhoff, Jackson, Newark, Overpeck, and Webber).

In addition to motivating half of the research papers in this special issue, EW3 also published two public-facing reports that drew upon and synthesized these *Environmental Research Letters*-published analyses. The first, *Freshwater Use by US Power Plants* (Averyt *et al* 2011) drew heavily upon research subsequently published in Averyt *et al* (2013a) to characterize the effects of power plant cooling on water resources across the United States, and the quality of information available to help public- and private-sector decision makers make water-smart energy choices. The second, *Water-Smart Power: Strengthening the US Electricity System in a Warming World* (Rogers *et al* 2013) provided a forward-looking assessment of the water implications of future electricity choices in the United States at national, regional, and local levels. Showing that low-carbon and low-water electricity production can go hand-in-hand, it drew substantially on the findings of the energy-water modeling and related research of Macknick *et al* (2012b), Sattler *et al* (2012), Clemmer *et al* (2013), Flores-López and Yates (2013) and Yates *et al* (2013a, 2013b, 2013c).

The release of these public-facing reports provided extensive opportunities for collaborators to discuss their findings with the media and to engage in outreach to a broad range of public and private-sector energy and water decision-makers and stakeholder at water-basin, state and national scales. As a result, for example, findings profiled by Averyt *et al* (2011) on the water consumption and withdrawal impacts of fuel type and cooling technology were incorporated into US National Climate Assessment (Melillo *et al* 2014) and a Congressional report on the connections between energy production and water use (Markey 2012) Outreach around this analysis also supported considerations for strengthening energy-water data collection and monitoring by the US Energy Information Administration and US Geological Survey.

As another example, the National Association of Regulatory Utility Commissioners drew upon the findings profiled in Rogers *et al* (2013) to adopt a landmark resolution on power plant water use (NARUC 2013). Informed by briefings and discussions with report authors, NARUC's resolution urges state and federal authorities to 'recognize the important role of water supply and related risks in electricity generation' and to 'take near and long-term steps to reduce water-electricity risks, including reducing the water intensity of power production'.

4. Looking forward

Public agencies such as the Departments of Energy (DOE) and Interior (DOI) in the United States and international development organizations like the Organization for Economic Co-operation and Development (OECD) have a stake in understanding the linkages of climate change, water use, and electricity production. DOI, for example, is the United States' largest wholesale supplier of water and the second largest producer of hydroelectric power. The 53 hydroelectric facilities operated by DOI's Bureau of Reclamation (BOR) are also managed to provide water for irrigation, recreation, and fish and wildlife benefits, as well as some projects that have flood control as a primary objective. BOR is required to consider all of these interests as it designs and implements its water resource projects in 17 western states. Over the past decade, climate change has become an integral factor in surface water management planning, and recognition of the need to better integrate electricity production planning and operations with water resource management in a changing climate is now emerging. DOE, for example, has created an integrated set of crosscutting research and development activities that supports the nation's transition to more resilient energy-water systems (DOE 2015) and is supporting initiatives such as the recently established US–China Clean Energy Research Center (CERC 2015).

Water resources are already being affected by climate change in many parts of the world and they are expected to undergo substantial additional changes through the end of this century. Most of the key vulnerabilities of the US energy sector to climate change involve water in some manner (DOE 2013). Many organizations that promote policies to improve economic and social well-being of people around the world classify development status, in part, according to a nation's access to water and electricity. Electricity production is one of the OECD's primary indicators of development status. Concerns about how climate change and future water availability will affect development potential have prompted the use of climate resilience screening tools for international investment by groups such as the World Bank and by some nations, such as Germany and the United States.

Several articles in this special issue suggest that water resources are expected to undergo substantial changes based on the global warming that results primarily from fossil energy-based carbon emissions. At the same time, the production of electricity from fossil fuels, nuclear power, and some renewable technologies (biomass, geothermal and concentrating solar power) can be highly water-intensive. Energy choices now and in the near future will have a major impact not just on the global climate, but also on water supplies and the resilience of energy systems that currently depend heavily on them.

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