Check for updates

Received: 18 July 2021 | Revised: 11 December 2021 | Accepted: 17 December 2021

DOI: 10.1002/wat2.1576

FOCUS ARTICLE

WIREs WATER WILEY

Water for energy: Characterizing co-evolving energy and water systems under twin climate and energy system nonstationarities

Emily Grubert | **Adrienne Marshall**

School of Civil and Environmental Engineering, Georgia Institute of Technology, Atlanta, Georgia, USA

Correspondence
Emily Grubert, Georgia Institute of Technology, Atlanta, GA 30332, USA.
Email: gruberte@gatech.edu

Present address
Adrienne Marshall, Hydrologic Sciences and Engineering Program, Colorado School of Mines, Golden, Colorado, USA

Edited by: Stuart N. Lane, Editor-in-Chief

Abstract

The energy system is a major water user, but understanding how much water is consumed and withdrawn for energy is a challenging empirical task: nonevaporative volumetric water use is not easily calculated from first principles. Water use also has impacts that differ in important ways depending on where water is abstracted and used, timing of use, and socioenvironmental context. Moreover, different decarbonization pathways and policy environments have very different water use implications. We currently face a crisis of twin nonstationarities in hydrology and energy systems that make understanding water use for energy critical for decision support as hydroclimate and energy systems change. Currently, water-for-energy data are highly uncertain and not centrally collected, which means researchers spend substantial effort collecting inventory data. Recent advances in impact assessment methods for water volumes focus largely on spatially resolved water scarcity evaluations, but robust conclusions can be elusive due to uncertain and low-metadata inventory information. As water-for-energy quantification efforts progress, research should emphasize decision support for energy system design, incorporating crucial hydrologic dynamics. Beyond the location of water use, relative scarcity, and potential competing uses, these include sub-daily to interannual temporal dynamics, the impacts of climate change on these dimensions, potential feedbacks between energy and water systems, and the impacts of hydrologic variability or change on policy-based incentive structures. This article reviews prior US-focused efforts to quantify water use for energy, highlights why these nonstationarities are analytically relevant with a brief policy case study, and highlights research needs for decision support under twin nonstationarities.

This article is categorized under:

Engineering Water > Sustainable Engineering of Water

Engineering Water > Planning Water

Engineering Water > Methods

KEYWORDS

energy, impact assessment, nonstationarity, water consumption, water withdrawal

 © 2022 Wiley Periodicals LLC.

1 | INTRODUCTION

Energy systems are changing rapidly, and must continue do so in order to meet climate stabilization targets (Grubert, 2020; Tong et al., 2019; Williams et al., 2021). Energy systems have water use requirements that are socially and environmentally impactful (Grubert & Sanders, 2018; Pfister et al., 2009, 2011; Pfister & Suh, 2015). However, the impacts of energy transitions on water availability and subsequent consequences are currently poorly understood and quantified (Chini & Delorit, 2021; Chowdhury et al., 2021). This issue is particularly relevant in the context of highly divergent energy transition pathways (Williams et al., 2021; Zacarias & Grubert, 2021). This gap has motivated efforts to use spatiotemporal resource information to evaluate the impact of energy system transitions, sometimes in conjunction with changing climate, on water resources (Clemmer et al., 2013; Grubert, 2020; Macknick, Sattler, et al., 2012; Miara et al., 2017, 2019; Sattler et al., 2012; Voisin et al., 2020), but robust and consistent analysis remains challenging.

Sustainability assessment methods like life cycle assessment (LCA) are increasingly used to characterize prospective multicriteria socioenvironmental impacts (Finnveden et al., 2009; Owens, 1997) associated with specific human activities and infrastructures in decision support contexts, including specifically for decarbonization decisions (Finkbeiner et al., 2010; Finkbeiner & Bach, 2021; Grubert, 2017b; Guinée et al., 2001, 2011; Heijungs et al., 2010; Seidel, 2016). Rigorously evaluating socioenvironmental impacts of volumetric water use in frameworks like LCA has been challenging for three major reasons. First, data are relatively scarce and difficult to validate, a challenge exacerbated by inconsistent and poorly defined terms related to "water use" (Gleick, 1994; Grubert et al., 2020; Grubert & Sanders, 2018; US DOE, 2006). Second, linking volumetric water use to specific activities and subsequent impacts is challenging, with contested methodologies (Gerbens-Leenes et al., 2021; Hoekstra, 2016, 2017; Pfister et al., 2009, 2017). Third, climate nonstationarity poses major challenges for robustly evaluating spatiotemporally variable impacts associated with water use (Chowdhury et al., 2021; Grubert & Webber, 2017). This nonstationarity is a particular challenge when medium-term to long-term projections of future impacts are informing path-dependent decisions today, as with assessments of alternative decarbonization pathways (Finkbeiner & Bach, 2021; Gibon et al., 2017; Hertwich et al., 2014; Tarroja et al., 2020).

Against this backdrop of existing challenges with data and impact assessment methods for water quantity in sustainability assessment, questions about water quantity used for energy systems are both salient and challenging for three major reasons. First, the anticipated water intensity of future energy systems is highly path dependent, given that resources expected to contribute heavily to energy system decarbonization range from very low (e.g., wind, solar photovoltaics) to very high (e.g., biofuel) water intensity (Finkbeiner & Bach, 2021; Gibon et al., 2017; Hertwich et al., 2014; Tarroja et al., 2020). Second, the impact of that water intensity is likely to be highly differentiated based on location (e.g., deserts vs. rainfed farmland), timing of use (e.g., summer vs. winter), water source (e.g., pumped groundwater vs. rain vs. ocean), water quality (e.g., treated potable vs. highly saline), and alternative demands (e.g., for crops or municipal supply). Because energy systems are subject to many constraints other than water use (e.g., resource quality, access to power lines, access to load, etc.), however, energy project siting is unlikely to be optimized around water alone. Limitations to water availability in specific points in space and time can impact electricity system reliability or greenhouse gas emissions (Ahmad, 2021; Tarroja et al., 2019). This issue could be exacerbated by increased dependence on specific, high water intensity resources for critical energy system functions that cannot be deferred. Third, water-for-energy research is currently decision-relevant: system design decisions are actively being made at multiple levels, so decision support tools are likely to find users. These decisions are occurring at a moment in which the energy transition is widely studied and well enough constrained to make specific scenario development and analysis feasible. The likely location, timing, source, quality, and alternative demands for water resources used for energy development pathways are at least directionally knowable due to practical constraints on energy infrastructure deployment, so scenarios can be developed with more specificity than volumetric water requirements alone. As such, water-for-energy requirements associated with energy transition deployment pathways represent an opportunity to develop and improve methods for evaluating spatiotemporally resolved environmental impacts under high uncertainty that could actively support decisions leading to path dependencies with serious potential consequences or opportunities for water management (Chini & Delorit, 2021; Peer et al., 2019; Peer & Sanders, 2018; Raptis et al., 2017, 2020; Tarroja et al., 2019, 2020). Success in this arena could also have longer term implications for sustainability assessment practice, as lessons learned from evaluating water for energy may be relevant to other noncarbon sustainability issues. While carbon dioxide has dominated assessment practice (Grubert, 2017a), water and other noncarbon outcomes share some important features. These include the facts that impacts are generally spatiotemporally variable even for the same flow or emission, and that universal, uniform relationships between marginal activity and marginal impacts might not exist (Burns & Grubert, 2021; Heijungs, 1998).

This review evaluates current and potential future practice for evaluating volumetric water use for energy systems in the context of two major nonstationarities: changes to the climate and changes to the energy system. Although much of this review is broadly applicable, we focus on the contiguous United States (CONUS). For highly empirical activities like sustainability assessment (Frischknecht & Rebitzer, 2005; Grubert & Brandt, 2019; Meron et al., 2016; Pfister et al., 2016; Pinsonnault et al., 2014), the failure of past observations to successfully characterize the future (Perrone et al., 2015) at the moment when these assessments are in highest demand due to ongoing efforts to redesign systems for sustainability is a major challenge. We highlight the role of these nonstationarities for practice (Section 2), describe the current status of water-for-energy inventory and impact assessment practice (Section 3), review hydrology-based considerations whose incorporation would enhance model capacity to provide decision support under uncertainty (Section 4), present a case study illustrating how interannual hydrologic variability and uncertainty could affect decarbonization incentives under a recent policy proposal (Section 5), and conclude with a discussion of future efforts and research needs on volumetric water use for energy.

2 | ENERGY AND CLIMATE NONSTATIONARITIES

Many challenges confront efforts to understand how energy systems impact water sustainability. We face twin nonstationarities as both water and energy systems evolve in response to anthropogenic climate change and efforts to mitigate it (Milly et al., 2008). Hydrologic systems are changing. For instance, Figure 1 uses daily freshwater discharge data from 703 stations in the HydroClimatic Data Network (HCDN) database in the United States, which are stations with minimal infrastructure or land use change affecting their streamflow trajectories (Lins, 2012), to show the change in median annual discharge (Figure 1a) and center of timing (CT, or the center of mass of streamflow, following Stewart et al., 2004, Figure 1b) from 1951–1980 to 1991–2020. Annual discharge has decreased in much of the US West and Southeast, and predominantly increased in the Northeast (Figure 1a). CT has predominantly shifted toward earlier streamflow timing in regions of the country that are snowmelt-dominated (Figure 1b). We therefore face hydrologic conditions that are changing in ways that vary spatially and temporally.

Simultaneously, the energy system is not only nonstationary but also actively being redesigned in response to the threat of climate change caused largely by the existing fossil fuel-based energy system (Intergovernmental Panel on Climate Change, 2014; Figure 2). The energy system has historically been reliably fossil-dominated to the degree that energy use (effectively, fossil energy use) has been a reasonable proxy for overall environmental impact for non-agricultural sectors (Huijbregts et al., 2010). Energy system nonstationarity, however, means that future socioenvironmental impacts of the energy system are unlikely to be easily proxied as the impacts of fossil fuel thermal energy systems. Socioenvironmental impacts of nonfossil energy resources, including water use (Grubert & Sanders, 2018), are diverse (Gibon et al., 2017) and likely driven more by land occupation than combustion in part due to an expected transition to primarily above-ground energy resources (Mulvaney, 2017).

The share of energy consumption originating from renewables has increased considerably over the last 20 years across most of the contiguous US. Figure 3 illustrates this transition using data from the US State Energy Data System (SEDS; EIA, 2020a, 2020b, 2020c, p. 20), to show the fraction of consumed energy originating from renewables in each state in 1995–1999 versus that in 2015–2019. These changes predominantly reflect renewable energy growth and are statistically significant based on a two-directional KS test (alpha = 0.1) through large swaths of the country (Figure 3). Understanding the concurrent impacts of this changing energy system against a backdrop of altered hydrology is an ongoing challenge.

We argue these two nonstationarities—climate-driven hydrology and energy—are crucial for contextualizing future environmental impacts, and specifically that understanding the role of volumetric water use for energy systems amidst these nonstationarities is critical for decision support as the future energy system is designed. Simultaneously, water has been and will continue to be strongly affected by climate change (Chadwick et al., 2020; Payne et al., 2004; Persad et al., 2020; Vorosmarty, 2000), while simultaneously being a required input for many energy systems that could be deployed for decarbonization (Efroymson et al., 2017; Tarroja et al., 2020; Williams et al., 2021). Yet, data and impact assessment methods for volumetric water use are subject to important limitations. The next section describes the current status of water-for-energy sustainability assessment.

3 | WATER-FOR-ENERGY INVENTORY AND IMPACT ASSESSMENT

Understanding volumetric water use for energy systems is decision-relevant. As of 2014, the US energy system accounted for an estimated 40% of water withdrawal and 10% of US water consumption (noting that irrigation accounts

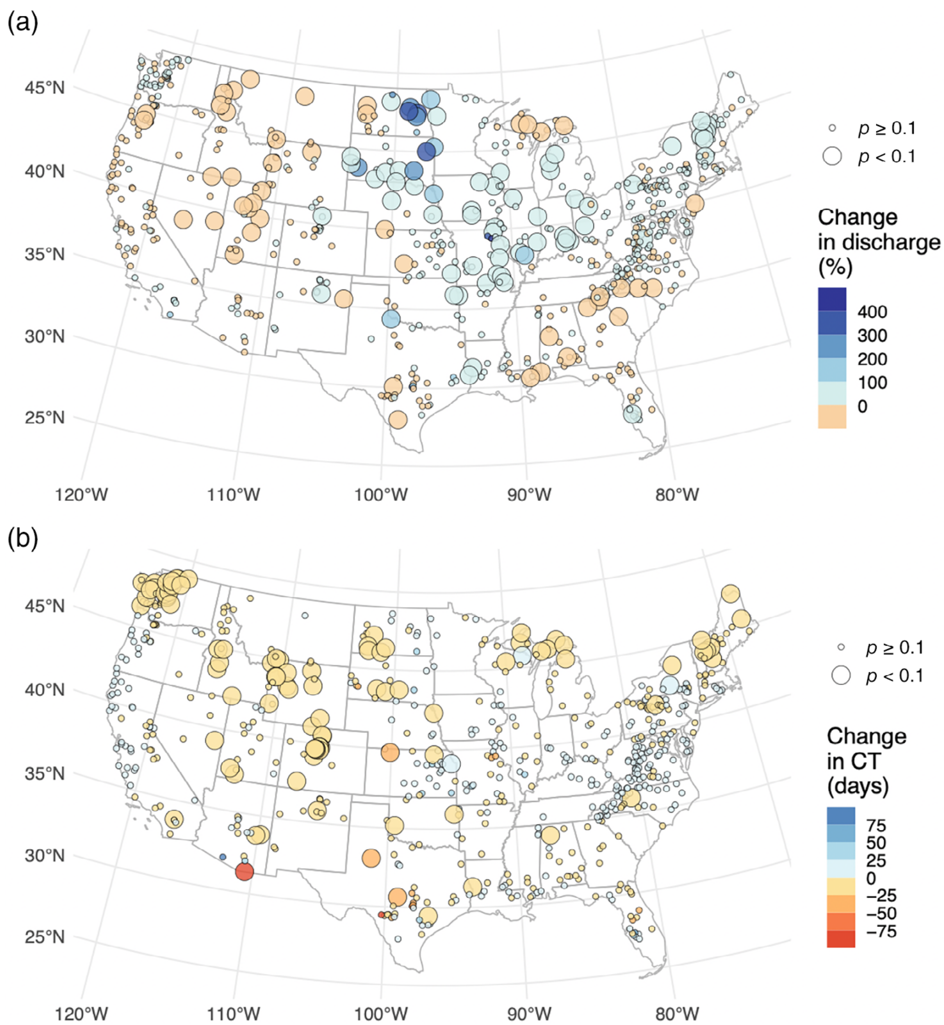

FIGURE 1 Change in median (a) annual discharge and (b) center of timing (CT) from 1951–1980 to 1991–2020. Large points in both panels indicate statistical significance ($p < 0.10$) using a two-directional Kolmogorov–Smirnov (KS) and a one-directional KS test for CT (null hypothesis: CT is later in the later time period); small points indicate no statistical significance

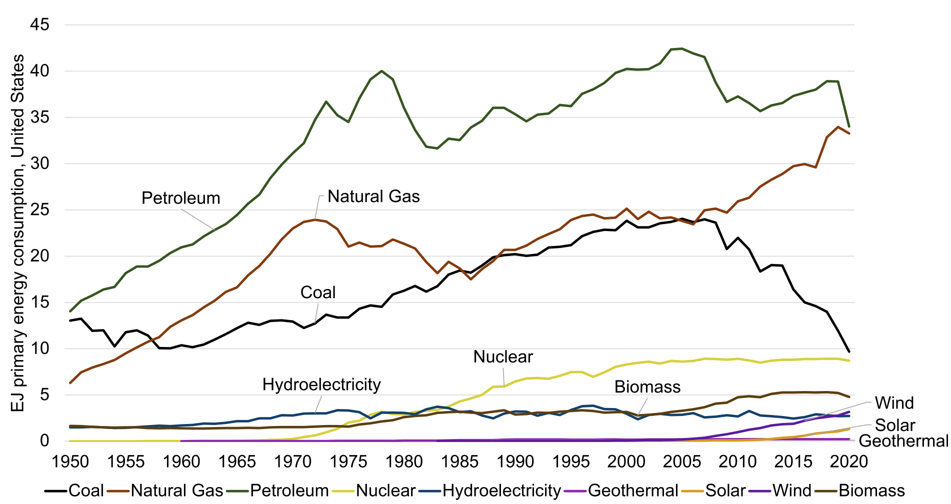

FIGURE 2 US primary energy consumption by fuel type, 1950–2020 (Data: EIA monthly energy review)

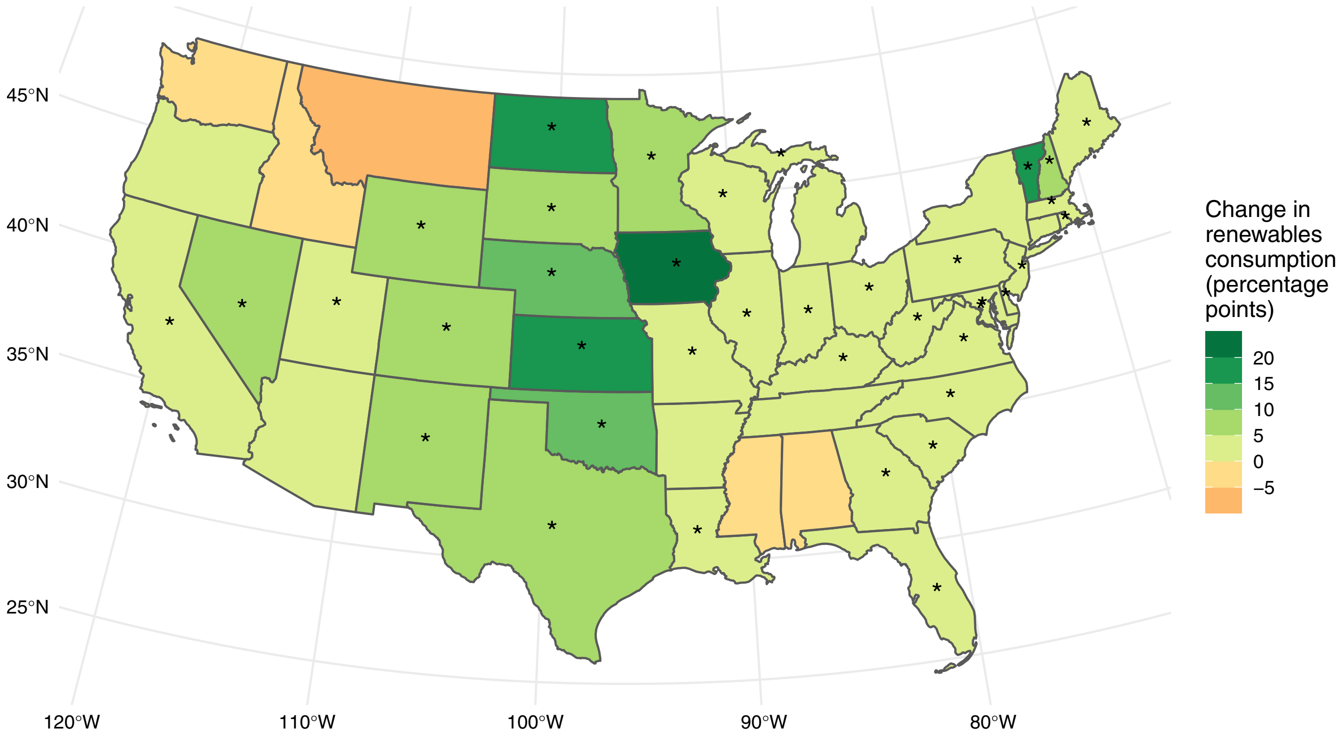

FIGURE 3 Change in the energy system from 1995–2019 to 2015–2019, showing change in renewables consumption as a fraction of total energy consumption by state, based on EIA SEDS. Asterisks identify states with statistically significant changes using a two-directional KS test ($p < 0.1$)

for about 80% of US total water consumption; Grubert & Sanders, 2018). Power plants with intensive water use characteristics, particularly consumptive use, are not always located in regions with abundant water (Figure 4).

Despite official projections that energy-related water use might remain relatively stable (though note that even in the conservative federal Annual Energy Outlook, water consumption is estimated to increase under a carbon tax; Zacarias & Grubert, 2021), energy systems associated with deep decarbonization pathways (Williams et al., 2021) could have factor of three differences in water consumption assuming stable water use intensities by resource (Grubert & Sanders, 2018). This assumption is unlikely to hold for at least some generation technologies. For example, both the water consumption and withdrawal intensity of hydropower production vary with reservoir elevation and surface area (Grubert, 2017a). Assuming static water consumption intensities, however, total annual energy-related water consumption under deep decarbonization scenarios ranges from about 4 billion cubic meters of freshwater for the 100% renewable scenario and 13 billion cubic meters for the low land scenario (compared with 13 billion cubic meters of freshwater for the 2014 system; Figure 5). In this section, we describe previous efforts to characterize water for energy use and impact assessment practices for water quantity.

3.1 | Water-for-energy inventories

Inventories of water use for energy production have not historically been officially documented at high spatiotemporal resolution; instead, this role has often been undertaken by academic research (Perrone et al., 2015). As such, by contrast with research that can rely on existing public information on energy flows and direct outputs, like combustion emissions (e.g., through the US Energy Information Administration [EIA] or Environmental Protection Agency [EPA]) to inform analysis, water-for-energy research relies on first generating or identifying inventory data. We note that not all countries have high quality energy and combustion data, and that many other areas of inquiry face similar data collection challenges. However, water-for-energy data are particularly scarce, and these data availability limitations affect research processes and decision support tools. LCA inventory databases like ecoinvent, GaBi, and others historically have excluded water quantity. By contrast, greenhouse gas emissions are arguably the most common sustainability

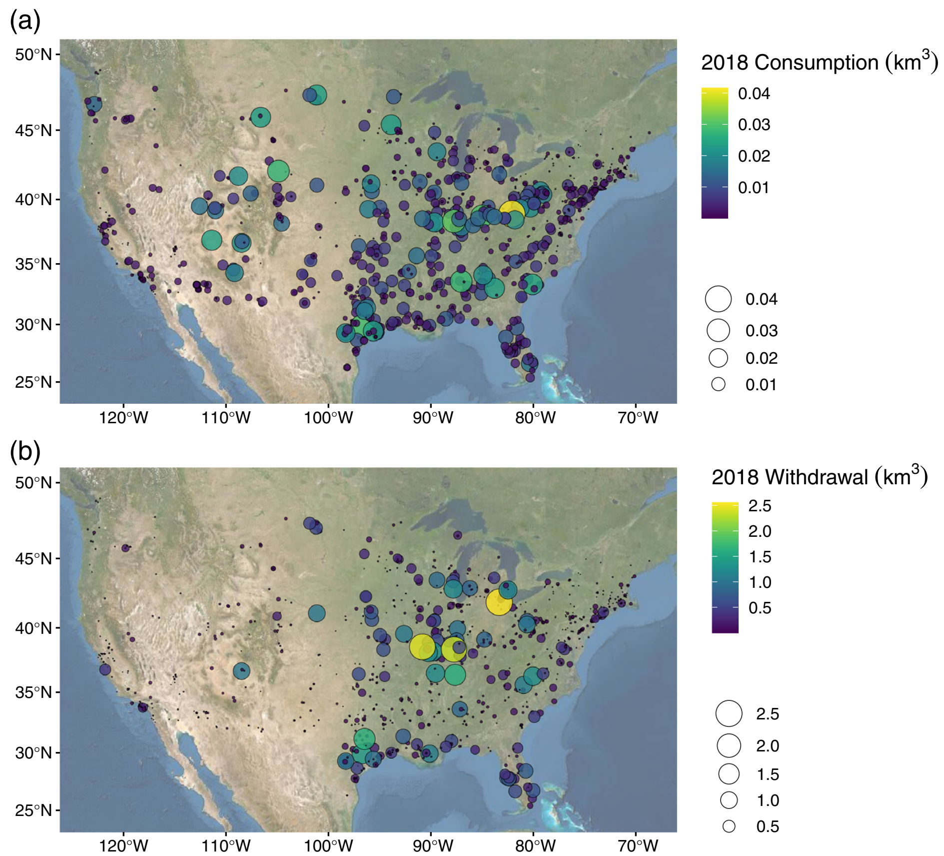

FIGURE 4 Estimated (a) consumption and (b) withdrawal of water from power plants in 2018. Data from (Grubert, 2020). Note that the color scale differs between panels. In each panel, both size and color are used to illustrate the respective value of interest

assessment indicator (Grubert, 2017a) and are widely and globally available due to international greenhouse gas inventory processes related to climate change (Intergovernmental Panel on Climate Change, 2014).

In the United States, estimates of water withdrawals and consumption for thermoelectric power, and water withdrawals for the mining and industrial sectors (undifferentiated by resource) are published within an eight-sector national water withdrawal estimate based on aggregated county data every 5 years (Dieter et al., 2018; Evenson et al., 2018; Maupin et al., 2014). National water consumption and hydroelectric power-related water use were reported up through the 1995 edition (Solley & US Geological Survey, 1998), and future Water Census efforts are expected to improve spatiotemporal temporal resolution for federal water use data products (Evenson et al., 2018). To date, however, more detailed data, including on uses of water for parts of the energy system beyond thermoelectric power generation, have typically been collected by researchers in a relatively ad hoc manner (Gleick, 1994; Grubert & Sanders, 2018; McManamay et al., 2021; Spang et al., 2014—though see US DOE [1980] as an early federal effort). Challenges with data scarcity have led to frequent republication and unit conversion, such that data provenance can be difficult to identify and validate as still relevant under current system conditions (Fthenakis & Kim, 2010; Grubert et al., 2020; Mekonnen et al., 2015; Vaca-Jiménez et al., 2021).

Data on the quantities of water used for energy systems are often published as total water withdrawn or consumed (Dieter et al., 2018; Maupin et al., 2014), as water-per-energy intensity factors (Macknick, Newmark, et al., 2012; Meldrum et al., 2013; Peer et al., 2019; Scherer & Pfister, 2016), or both (Gleick, 1994; Grubert & Sanders, 2018; Marston et al., 2018). Water-per-energy intensity factors are not always well posed theoretically (e.g., water used to drill an oil well is proportional to the size of the well, not its production), but might be used that way in practice (Grubert & Sanders, 2018; Peer et al., 2019). Efforts have differed both in scope (e.g., electricity generation—Macknick, Newmark, et al., 2012; Peer & Sanders, 2016, 2018; Pfister et al., 2011; single fuel cycles—Klise et al., 2013; Nicot & Scanlon, 2012; Scanlon et al., 2014; Wu et al., 2014; or snapshots of energy systems—Gleick, 1994; Grubert & Sanders, 2018) and in categorization, with particular differences observed in the way that characterization studies have dealt with the fact that "water" is not fully descriptive of the resource in question (Boulay et al., 2011; Grubert et al., 2020). For example,

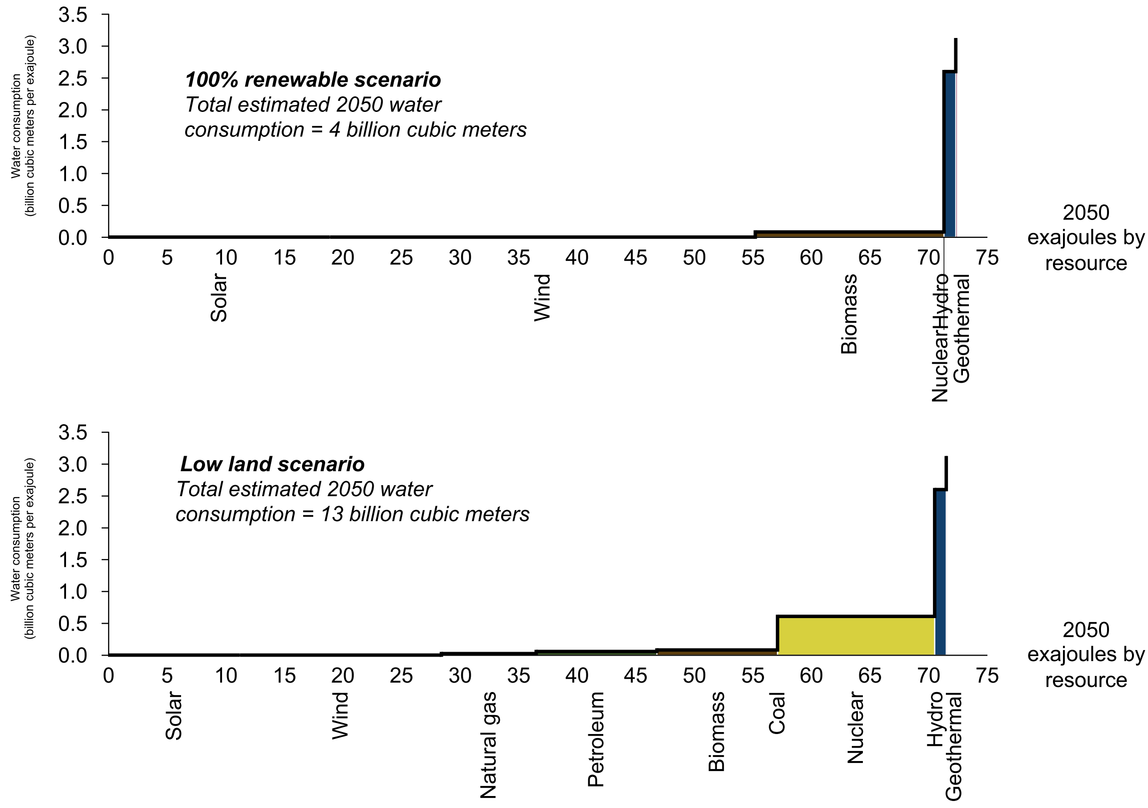

FIGURE 5 Projected 2050 water consumption for US decarbonization pathways from Williams et al., 2021, assuming static consumptive water intensities from Grubert and Sanders, 2018

choices to evaluate only freshwater (Raptis et al., 2020) versus multiple water qualities (Grubert & Sanders, 2018), and how those choices are described and justified, vary by study. One proposal for water categorization includes 17 separate categories (Boulay et al., 2011): high resolution is desirable but can be evasive in practice given water data quality constraints (Grubert et al., 2020; Perrone et al., 2015). Similarly, choices to include rain water (in water footprinting parlance, green water [Hoekstra et al., 2011]) or polluted water volumes (gray water [Hoekstra et al., 2011]) vary by study (Chini et al., 2020; Marston et al., 2018), though green water is mainly relevant for systems including agriculture and/or silviculture (Grubert et al., 2020). When the water use of electricity in a specific area is the quantity of interest, challenges also arise in determining the relevant geographic attribution of water used for electricity (Siddik et al., 2020).

One major conflict in volumetric water use assessment (Gerbens-Leenes et al., 2021) regards the water footprinting method's preference for volumetric inventory measures alone, treating water use as resource depletion (Hoekstra, 2016) due to the potential for virtual water trade to allocate such use based on availability (Chapagain & Hoekstra, 2008; Chini et al., 2018; He et al., 2019). Contrast this to the LCA method's emphasis not on volumes as a fungible metric of global water productivity but on impacts, based on volumetric inventory data that have been transformed via impact assessment metrics that aim to account for local use contexts (Pfister et al., 2017). Given our interest in reviewing multi-criteria environmental impacts (the impact assessment) associated with volumetric water use for energy systems (the inventory), we discuss impact assessment in Section 3.2.

3.2 | Water impact assessment

The socioenvironmental impacts of volumetric water use for energy systems vary based on context (Pfister et al., 2011), including location, timing across multiple scales, alternative potential uses for the water, and water quality impacts. Despite its widely acknowledged relevance for sustainability evaluations (Pfister et al., 2016), and the high priority that people place on water relative to other environmental resources (Grubert, 2017b), water quantity has historically been excluded or inconsistently addressed as an impact category in LCA (Bare, 2002; Owens, 1997; Pfister et al., 2016)—likely contributing to the co-development of inventory-oriented water footprinting as a separate method (Hoekstra, 2017; ISO, 2014, though note that ISO 14046 recognizes both single-category and multicategory impact assessment as valid for water footprinting). Potential reasons for this exclusion include challenges associated with gathering robust and generalizable inventory data (Section 3.1), appropriately defining and distinguishing among water and water use types (Grubert et al., 2020; Hoekstra et al., 2011; Perrone et al., 2015; Pfister et al., 2016), and rigorously representing the conditions under which volumetric water use has the potential to create impacts (Hoekstra, 2016; Pfister et al., 2009, 2017). One early review of impact assessment approaches notes the need for differentiating water by origin, region, and quality (Kounina et al., 2013).

The Water Use in Life Cycle Assessment (WULCA) group, active since 2007, is one major effort to establish a comprehensive impact assessment method for water quantity in LCA (Boulay et al., 2015). In 2018, the WULCA published its consensus characterization model for water scarcity, "assessing impacts of water consumption based on available water remaining" (AWARE), which addresses the core question "What is the potential to deprive another user (human or ecosystem) when consuming water in this area?" (Boulay et al., 2018). This regionalized water scarcity impact assessment method is effectively a distance-to-target approach, in which impacts are ranked as more important when they are further from a designated acceptable standard. It is intended to enable LCA to more comprehensively evaluate the impacts of water use than quantity alone would (Boulay et al., 2018). Other efforts focus on impacts other than water scarcity in general: for example, Damiani et al. (2021) propose regionalized characterization factors for river habitat change potential, arguing also for mechanistic watershed and sub-watershed level modeling. They further argue that high spatial resolution in characterization factors can mitigate a lack of metadata describing where impacts from volumetric water use might occur, as the characterization factors help quantify potential uncertainty. Lin and Chiueh (2021) also focus on high spatial resolution data, emphasizing the distribution of damages across users to reflect impacts at the point of supply might not be the same as impacts at the point of consumption. To date, water impact assessment methods have largely focused on impacts of freshwater consumption and the role of spatial differentiation.

As efforts to better inventory and evaluate impacts of volumetric water use proceed, ongoing investigation of whether methods are fit-for-purpose is warranted. The next section takes a hydrology-based view to review the types of information likely to be useful for making decisions about large water-using systems.

4 | HYDROLOGY IN WATER IMPACT ASSESSMENT

Water systems are changing. Flow regimes in climate changed and managed basins are not the same as observed for pre-industrial natural water systems, and decision support tools presenting volumetric water sustainability assessments should consider the role of hydrology-based considerations like timing, seasonality, and other contexts on the actual impact of volumetric water use (Chini & Delorit, 2021; DeFlorio et al., 2021; Rupp et al., 2021). Understanding the socioenvironmental impacts of volumetric water use—both consumption and withdrawal—for energy and other water-using systems in a manner that reflects hydrologic realities requires identifying where water is used, opportunity costs for other users, and when it is used across multiple time scales. Of these, methods and data enabling evaluation of timing impacts, from sub-daily to decadal scales, are the least developed to date.

4.1 | Location of water use

As already recognized by water quantity impact assessment methods (Section 3.2), water use for energy systems has significantly differentiated impacts depending on the location of water source and use. Water is much more scarce in some locations than others, with greatest scarcity relative to population reported in arid and semiarid regions and in densely populated parts of the tropics and temperate regions (Vorosmarty, 2000). However, this water scarcity also varies depending on hydraulic infrastructure, which can considerably mitigate scarcity (McDonald et al., 2014; Padowski & Jawitz, 2012). In the CONUS, for example, water scarcity is generally greatest in the southwestern United States (Padowski & Jawitz, 2012). Globally, the regions of greatest potential water scarcity include the southwest United States, parts of India and eastern China, the Arabian Peninsula, and Australia (Padowski & Gorelick, 2014; Vorosmarty, 2000).

4.2 | Alternative uses for water

As the AWARE method emphasizes (Boulay et al., 2018), potential alternative uses for water with which the energy use is competing will also affect our understanding of the impacts of water use for energy. Competition may be reduced in withdrawal as compared with consumptive use cases. However, the infrastructure of water use for energy can complicate the neat divide between consumptive and withdrawal use types. For instance, water flowing through turbines for hydropower is typically considered as withdrawal rather than consumption (or excluded from consideration; Grubert & Sanders, 2018), but when diversions are present, may dewater extensive stretches of river nonetheless (McManamay et al., 2016). Justice and equity are also important components of understanding the impacts of water use for energy, including indigenous rights and cultural values (Cosens, 2016; Curley, 2021; Sproat, 2011; Ween & Colombi, 2013; Wilson et al., 2021), water scarcity for marginalized groups (Meshel, 2018), and employment (Patrizio et al., 2020).

4.3 | Timing of water use

Less incorporated to current impact assessment practice is the fact that the timing of water use for energy affects its impact at multiple temporal scales. At the seasonal scale, water availability generally has distinctive seasonal patterns that vary regionally. In snowmelt-dominated regions, these seasonal patterns are dominated by snowmelt timing (D. Li et al., 2017); in regions with smaller snow-to-precipitation ratios, the timing of water availability is more governed by precipitation and watershed hydrology (Beven, 1983; Lucey et al., 2020). In many regions, a surplus of water in certain seasons is paired with a deficit in others, with water management designed in part to reduce this seasonality. Reservoirs modify the timing of water availability, generally capturing runoff while water is plentiful and reserving it for periods of seasonal scarcity; their ability to capture flows ranges from months to years in the United States (Graf, 1999; Langbein, 1959). Water use for energy may be more impactful or less reliable in seasonal periods of lower water availability, which can have serious impacts on energy service provision (Ahmad, 2021; Tarroja et al., 2019). Recent commentaries have proposed that these seasonality issues be addressed by modifying water footprint estimates seasonally (Chini & Delorit, 2021).

Sub-daily temporal patterns of water use for energy are also impactful. While water does not have the same need for instantaneous supply–demand matching as electricity, diurnal use patterns can affect the impact of water use. Likely the best understood example of this is in hydropower operations, where the ecological impacts of rapid ramping are well recognized (Cushman, 1985; Richter & Thomas, 2007) and empirical evidence suggests that such limitations constrain daily hydropower operational patterns (Marshall & Grubert, n.d.). Important elements of diurnal flow variation downstream of hydropower facilities include the timing, frequency, duration, magnitude, and antecedent flow conditions of pulsed flows (Young et al., 2011). The impacts of sub-daily water use patterns for other fuel types are, to our knowledge, much less well studied.

Finally, interannual variability in water availability can be as much of a challenge in water management as low average water availability and is common in low-income regions globally (Hall et al., 2014). This interannual variability varies spatially; globally and in the United States, interannual variability of water availability and scarcity is generally highest in the driest regions (Greve et al., 2018; Zou et al., 2018). An important consideration is whether the extent to which water consumed by different energy technologies varies interannually. For instance, evaporation from reservoir surfaces could be high in warmer or drier years when evaporative demand is higher, or lower when reservoir surface areas are lower, limiting the available area for evaporation (Y. Li et al., 2020). Other energy technologies could similarly vary interannually in their water use, but as with sub-daily variability, this is less well documented. This variability also limits the stationarity of water consumption intensities of energy processes

4.4 | Impacts of climate change on water availability

Changing climate is altering water scarcity and the impacts of water use for energy in ways that vary regionally. While climate models and observations both consistently indicate warmer temperatures, observed and projected changes in precipitation are much more variable across space and climate models in both magnitude and direction (Cook et al., 2020; IPCC, 2013), though an increase in precipitation extremes is well-documented (Madakumbura et al., 2021; NCA, 2018; O'Gorman & Schneider, 2009; Prein et al., 2017). Despite uncertainty in projected changes in precipitation, some consistent trends in water availability are nonetheless well understood. In snow-dominated regions, a shift from snow to rain (Klos et al., 2014) is already reducing snowpack and snow extent (Hamlet et al., 2005; Mote et al., 2018), with these trends projected to continue (Ashfaq et al., 2013; Fyfe et al., 2017; Mankin & Diffenbaugh, 2015; Marshall et al., 2019). These declines in snowpack are advancing snowmelt and streamflow timing in both observations and projections (Stewart et al., 2004, 2005). Due to the importance of these changes in snowpack, projected changes in hydrology are generally largest in mid-latitude to high-latitude, snow-dominated basins (Nijssen et al., 2001). Across the Northern Hemisphere, runoff is predominantly projected to decline in April through September, particularly in locations with projected runoff increases in October through March (Cook et al., 2020). In these snowmelt-dominated regions, reservoirs are often not able to capture the earlier runoff associated with reduced snowpack, resulting in less capture of water and greater runoff to the ocean (Barnett et al., 2005). In the continental US these changes are predominantly resulting in increases in streamflow in much of the Eastern US, with decreases in the western US and earlier streamflow timing in the west (IPCC, 2013; Krakauer & Fung, 2008; Figure 1).

Climate change is also altering temporal hydrologic variability in ways that could intersect with temporal variations in water demand from energy infrastructure. For instance, annual streamflow in the lowest quartile of years has declined more than the median or mean streamflow in the Pacific Northwest (Lins & Slack, 1999; Luce & Holden, 2009), and frequency of no-flow days is increasing in streams in both the United States and Australia (Sauquet et al., 2021). To the extent that energy infrastructure demands more water in drier years or seasons, this could exacerbate scarcity limitations; in contrast, if energy infrastructure is flexible about water demand, these limitations may be less problematic. Projections of high flow extremes vary spatially and can be complicated by, for instance, the impacts of changing synchrony among tributaries to a larger river (Rupp et al., 2021); see Brunner et al. (2021) for a detailed treatment of challenges and advances in flood and drought prediction. Interannual hydrologic sequences are also expected to change, with more frequent multiyear snow droughts in the western US (Marshall et al., 2019) and transitions from very wet to very dry years in California (Swain et al., 2018). The impacts of these transitions on energy development pathways are not currently well understood.

These changes in the total quantity and spatial and temporal distributions of water will alter water availability for energy. A considerable body of literature evaluates the impacts of climate change on hydropower availability, generally finding decreases in availability though estimates of the effect size vary widely depending on geography and methods (Bartos & Chester, 2015; Kao et al., 2015; van Vliet, Sheffield, et al., 2016; van Vliet, Wiberg, et al., 2016; Voisin et al., 2020). Other potential effects of climate change on water availability for energy include increases in demand for thermal power plant cooling water; see Szinai et al. (2020) for a detailed framework and case study of California.

5 | CASE STUDY: DECARBONIZATION POLICY, CLIMATE CHANGE, AND HYDROPOWER

The Clean Electricity Performance Program (CEPP) proposed in 2021 (but not enacted) highlights one example of how uncertainty associated with climate and energy system nonstationarities could affect resource management at the water-energy nexus, illustrating the importance of incorporating these nonstationarities into standard analytical practice for decision support. Under the CEPP, utilities would have received \$150/MWh for a portion of their clean electricity generation in year i if they increased the share of clean electricity serving load by at least 4% per year (averaging over up to 3 years; Equation (1)), or paid a penalty of \$40/MWh for falling short of the 4% annual increase in year i (Equation (2)).

$$\text{Payment}_i = \$150 \times [\text{clean MWh}_i - (0.015\text{load}_i + \text{clean MWh}_{i-1})] \tag{1}$$

$$\text{Penalty}_i = \$40 \times \text{load}_i \times [0.04 + (\text{clean electricity share}_{i-1} - \text{clean electricity share}_i)] \tag{2}$$

Equation (2) would not have applied if the clean electricity share is 85% or above and has not dropped since the prior year.

How would the CEPP have affected a utility that is heavily reliant on hydropower, with high climate-related uncertainty, particularly given climate change-driven nonstationarity? Consider Idaho Power Company, which uses hydropower as its dominant energy resource, and the only clean energy source for which it is listed as the Operator on Form EIA 923 (EIA, 2020b). Using the simplification that the utility's load in a given year is equal to generation by assets for

TABLE 1 Hypothetical CEPP payments to utility based on historical capacity and generation data from the Energy Information Administration forms 860 and 923 (EIA, 2020a, 2020b)

Year	Hydropower capacity (MW)	Total generation as operator (TWh)	Hydropower generation as operator (TWh)	Clean generation as operator (TWh)	Clean electricity share (%)	Hypothetical CPP payments to utility (million $)
2015	1706.8	7.99	5.91	5.91	74.0	—
2016	1706.8	8.13	6.41	6.41	78.8	56
2017	1703.8	10.4	8.90	8.90	85.6	350
2018	1793.4	10.1	8.68	8.68	86.0	0
2019	1793.4	10.4	8.29	8.29	79.7	−43
2020	1796.6	9.07	6.97	6.97	76.8	−25

which it is listed as the Operator and assuming no deferrals, Idaho Power's payments or penalties would vary widely under the CEPP due to hydropower generation variability even under recent historical conditions (Table 1). Assuming the CEPP used 2015 as a baseline and took effect in 2016, Idaho Power would have received net payments of about $340 million for the 2015–2020 period—mostly due to extremely large payments of $350 million in a particularly wet year (2017). By contrast, assuming the CEPP used 2018 as a baseline and took effect in 2019, Idaho Power would have penalties of tens of millions of dollars per year, despite very little change to its installed clean energy capacity between 2015 and 2020 (Table 1).

The existence of proposals like the CEPP reflects that energy system nonstationarity is likely to be at least partly driven by explicit policy goals, including President Biden's target of full power sector decarbonization by 2035. As such, the intersection between climate nonstationarity and enforcement mechanisms for regulatory or other policy actions associated with decarbonization goals is likely to create new resource management challenges for water-dependent power utilities. These challenges are likely particularly significant for hydroelectricity, due to its large hydroclimatically driven variability. The hypothetical example here illustrates payment variability under recent historical climatic conditions; yet the impact of climate nonstationarity on hydropower production is complex, with impacts that vary regionally and remain an active area of research with significant uncertainties (Carlino et al., 2021; Gernaat et al., 2021; Hill et al., 2021; Paltán et al., 2021; Voisin et al., 2020).

From an energy-water nexus perspective, one major risk is that water releases for power generation could become significantly more financially valuable relative to other water uses. In the Idaho Power hypothetical above, for example, not releasing more water for power in 2019 could cost tens of millions of dollars. This dynamic poses an extremely challenging conundrum for water managers who might have faced a decision between adhering to ecological flow agreements or becoming liable for large CEPP penalties. Similar dynamics could emerge for other water intensive renewable energy resources, though likely not to the same extent given the anticipated and sometimes extreme volatility of interannual variability in hydropower generation. Balancing uncertainty about zero-GHG energy system costs with uncertainty in seasonal- to multiyear climatological projections could become critically important for management at the energy-water nexus as decision makers consider whether to invest in new zero-GHG generation capacity or rely on hydropower. Moreover, while considerable research effort has been directed toward understanding retrospective quantities of water used per unit of power generation across fuel types (Nature Sustainability Editorial Board, 2021) and considerable uncertainties remain, improved knowledge of the interaction between policy changes and prospective energy and water nonstationarities is a critical area for further research.

6 | CONCLUSION

The relevance of volumetric water use for energy systems, and for sustainability more broadly, has received increasing attention by the scientific literature in the recent past. Although this review emphasizes the contiguous US, the scarcity of rigorous, up-to-date, and high-quality data on water volumes withdrawn, consumed, and transformed by energy systems, and the major challenges associated with generating robust characterizations of decision-relevant impacts of this water use, are general challenges. Recent efforts to understand water use impacts associated with energy systems (and other uses) have largely focused on collecting inventory data. Some recent work has considered inventories or impact assessments, with efforts to include spatiotemporal resolution or conditions requiring high resolution spatiotemporal data (Chini & Delorit, 2021; Chowdhury et al., 2021; Grubert, 2020; Logan et al., 2021; Lubega & Stillwell, 2017; Pfister et al., 2020). Increasingly, volumetric water-for-energy research is demanded as an input for long-term future system design as opposed to near-term system characterization. This is particularly important given the highly divergent potential water demands from energy systems associated with decarbonization pathways and the anticipated impacts of climate change on water availability and its interannual variability. Providing energy is a nondiscretionary activity, and as such, the twin impacts of energy and climate nonstationarity on water systems should be carefully investigated before committing to energy systems that lock in reliance on water quantities with specific quality, timing, and location needs. Deep decarbonization activities like carbon capture (Wang et al., 2021), CO_2 recovery from biomass (Williams et al., 2021), hydrogen production (Grubert, 2009), and others could have meaningful but as-yet poorly understood water requirements, as could new mining activities (e.g., for lithium batteries) associated with the energy system. Currently, energy systems in the United States both consume and withdraw water in regions that are quite water scarce (Figure 4). Understanding the extent to which future decarbonization and energy system development pathways mitigate or exacerbate a mismatch between water demand and availability in either space or time is an important element that should be included in energy systems analysis.

Future work on water use for energy systems will likely need to include specific attention to hydrologic dynamics in addition to issues of baseline scarcity and regionalization. Climate change dynamics add major uncertainties to these assessments, particularly because long-lived energy infrastructures could be in place long enough to experience significant hydrologic changes and because other water users could also face changing pressures. Water for energy studies can play an important role in informing energy system design along decarbonization pathways, particularly if data collection, analysis, and impact assessment are designed specifically to enhance decision support. With that in mind, we suggest the following unanswered questions for which more research may be needed for decision support:

1. How do water intensities of different fuel types vary with hydroclimate conditions, either across space or time? Temporal scales of interest include sub-daily, seasonally, and interannual variability.
2. What is the elasticity of energy production to interannual variations in water availability for different fuel types and energy systems?
3. How do constraints due to water availability compare with nonwater constraints on energy development pathways?
4. What hydroclimatic conditions could result in threshold responses in the energy system? For instance, what are the hydroclimate conditions that would lead to widespread deadpool in the hydropower system?
5. How might historical or simulated future hydrologic variability impact incentive structures in anticipated or unanticipated ways under different clean energy policy structures (as illustrated in Section 5)?
6. Are there feedbacks between water and energy nonstationarities? That is, are there circumstances in which changes in water use by novel energy systems will alter energy capacity or generation?

Much as the recognition of nonstationary water supplies has prompted calls for new statistical paradigms (Milly et al., 2008), we suggest that co-evolving nonstationary energy and water systems require new evaluations of how water is used for energy, how those relationships have varied historically, and how changing climate and policy environments may fundamentally alter relationships between water and energy use. Water and energy are both critical resources supporting human existence that are undergoing paradigm-shifting changes. These changes should also motivate paradigm shifts in our analytical approaches in order to ensure we identify these challenges with adequate time to respond in ways that support sustainable use of both energy and water resources.

CONFLICT OF INTEREST

There are no conflicts of interest to declare.

AUTHOR CONTRIBUTIONS

Emily Grubert: Conceptualization (lead); data curation (supporting); investigation (equal); writing – original draft (equal); writing – review and editing (lead). **Adrienne Marshall:** Data curation (lead); investigation (equal); visualization (lead); writing – original draft (equal); writing – review and editing (supporting).

DATA AVAILABILITY STATEMENT

Data sharing is not applicable to this article as no new data were created or analyzed in this study.

ORCID

Emily Grubert https://orcid.org/0000-0003-2196-7571
Adrienne Marshall https://orcid.org/0000-0001-5555-2548

RELATED WIRES ARTICLES

Leveraging the water-energy nexus to derive benefits for the electric grid through demand-side management in the water supply and wastewater sectors
A review of the energy-carbon-water nexus: Concepts, research focuses, mechanisms, and methodologies

REFERENCES

Ahmad, A. (2021). Increase in frequency of nuclear power outages due to changing climate. *Nature Energy*, *1–8*, 755–762. https://doi.org/10.1038/s41560-021-00849-y

Ashfaq, M., Ghosh, S., Kao, S.-C., Bowling, L. C., Mote, P., Touma, D., Rauscher, S. A., & Diffenbaugh, N. S. (2013). Near-term acceleration of hydroclimatic change in the western U.S. *Journal of Geophysical Research: Atmospheres*, *118*(19), 10676–10693. https://doi.org/10.1002/jgrd.50816

Bare, J. C. (2002). TRACI: The tool for the reduction and assessment of chemical and other environmental impacts. *Journal of Industrial Ecology*, *6*, 49–78. https://doi.org/10.1162/108819802766269539

Barnett, T. P., Adam, J. C., & Lettenmaier, D. P. (2005). Potential impacts of a warming climate on water availability in snow-dominated regions. *Nature*, *438*(7066), 303–309. https://doi.org/10.1038/nature04141

Bartos, M. D., & Chester, M. V. (2015). Impacts of climate change on electric power supply in the Western United States. *Nature Climate Change*, *5*(8), 748–752. https://doi.org/10.1038/nclimate2648

Beven, K. (1983). Surface water hydrology—Runoff generation and basin structure. *Reviews of Geophysics*, *21*(3), 721–730. https://doi.org/10.1029/RG021i003p00721

Boulay, A.-M., Bare, J., Benini, L., Berger, M., Lathuillière, M. J., Manzardo, A., Margni, M., Motoshita, M., Núñez, M., Pastor, A. V., Ridoutt, B., Oki, T., Worbe, S., & Pfister, S. (2018). The WULCA consensus characterization model for water scarcity footprints: Assessing impacts of water consumption based on available water remaining (AWARE). *The International Journal of Life Cycle Assessment*, *23*(2), 368–378. https://doi.org/10.1007/s11367-017-1333-8

Boulay, A.-M., Bare, J., De Camillis, C., Döll, P., Gassert, F., Gerten, D., Humbert, S., Inaba, A., Itsubo, N., Lemoine, Y., Margni, M., Motoshita, M., Núñez, M., Pastor, A. V., Ridoutt, B., Schencker, U., Shirakawa, N., Vionnet, S., Worbe, S., … Pfister, S. (2015). Consensus building on the development of a stress-based indicator for LCA-based impact assessment of water consumption: Outcome of the expert workshops. *The International Journal of Life Cycle Assessment*, *20*, 577–583. https://doi.org/10.1007/s11367-015-0869-8

Boulay, A.-M., Bouchard, C., Bulle, C., Deschênes, L., & Margni, M. (2011). Categorizing water for LCA inventory. *The International Journal of Life Cycle Assessment*, *16*(7), 639–651. https://doi.org/10.1007/s11367-011-0300-z

Brunner, M. I., Slater, L., Tallaksen, L. M., & Clark, M. (2021). Challenges in modeling and predicting floods and droughts: A review. *WIREs Water*, *8*(3), e1520. https://doi.org/10.1002/wat2.1520

Burns, D., & Grubert, E. (2021). Attribution of production-stage methane emissions to assess spatial variability in the climate intensity of US natural gas consumption. *Environmental Research Letters*, *16*(4), 044059. https://doi.org/10.1088/1748-9326/abef33

Carlino, A., De Vita, A., Giuliani, M., Zamberletti, P., Capros, P., Recanati, F., Kannavou, M., & Castelletti, A. (2021). Hydroclimatic change challenges the EU planned transition to a carbon neutral electricity system. *Environmental Research Letters*, *16*. https://doi.org/10.1088/1748-9326/ac243f

Chadwick, C., Gironás, J., Barría, P., Vicuña, S., & Meza, F. (2020). Assessing reservoir performance under climate change. When is it going to be too late if current water management is not changed? *Water*, *13*(1), 64. https://doi.org/10.3390/w13010064

Chapagain, A. K., & Hoekstra, A. Y. (2008). The global component of freshwater demand and supply: An assessment of virtual water flows between nations as a result of trade in agricultural and industrial products. *Water International*, *33*(1), 19–32. https://doi.org/10.1080/02508060801927812

Chini, C. M., & Delorit, J. D. (2021). Opportunities for robustness of water footprints in electricity generation. *Earth's Future*. *9*(7). https://doi.org/10.1029/2021EF002096

Chini, C. M., Djehdian, L. A., Lubega, W. N., & Stillwell, A. S. (2018). Virtual water transfers of the US electric grid. *Nature Energy*, *3*(12), 1115–1123. https://doi.org/10.1038/s41560-018-0266-1

Chini, C. M., Logan, L. H., & Stillwell, A. S. (2020). Grey water footprints of U.S. thermoelectric power plants from 2010–2016. *Advances in Water Resources*, *145*, 103733. https://doi.org/10.1016/j.advwatres.2020.103733

Chowdhury, A. F. M. K., Dang, T. D., Nguyen, H. T. T., Koh, R., & Galelli, S. (2021). The greater Mekong's climate-water-energy nexus: How ENSO-triggered regional droughts affect power supply and CO2 emissions. *Earth's Futures*, *9*(3), e2020EF001814. https://doi.org/10.1029/2020EF001814

Clemmer, S., Rogers, J., Sattler, S., Macknick, J., & Mai, T. (2013). Modeling low-carbon US electricity futures to explore impacts on national and regional water use. *Environmental Research Letters*, *8*(1), 015004. https://doi.org/10.1088/1748-9326/8/1/015004

Cook, B. I., Mankin, J. S., Marvel, K., Williams, A. P., Smerdon, J. E., & Anchukaitis, K. J. (2020). Twenty-first century drought projections in the CMIP6 forcing scenarios. *Earth's Futures*, *8*(6), e2019EF001461. https://doi.org/10.1029/2019EF001461

Cosens, B. (2016). The Columbia River treaty: An opportunity for modernization of basin governance. *Colorado Natural Resources, Energy and Environmental Law Review*, *27*(1), 17.

Curley, A. (2021). Infrastructures as colonial beachheads: The Central Arizona project and the taking of Navajo resources. *Environment and Planning D: Society and Space*, *39*(3), 387–404. https://doi.org/10.1177/0263775821991537

Cushman, R. M. (1985). Review of ecological effects of rapidly varying flows downstream from hydroelectric facilities. *North American Journal of Fisheries Management*, *5*, 330–339. https://doi.org/10.1577/1548-8659(1985)5<330:ROEEOR>2.0.CO;2

Damiani, M., Roux, P., Loiseau, E., Lamouroux, N., Pella, H., Morel, M., & Rosenbaum, R. K. (2021). A high-resolution life cycle impact assessment model for continental freshwater habitat change due to water consumption. *Science of the Total Environment*. *782*, 146664. https://doi.org/10.1016/j.scitotenv.2021.146664

DeFlorio, M., Ralph, F. M., Waliser, D. E., Jones, J., & Anderson, M. L. (2021). Better subseasonal-to-seasonal forecasts for water management. *EoS*, *102*. https://eos.org/features/better-subseasonal-to-seasonal-forecasts-for-water-management

Dieter, C., Maupin, M., Caldwell, R. R., Harris, M. A., Ivahnenko, T. I., Lovelace, J., Barber, N., & Linsey, K. (2018). *USGS estimated use of water in the United States in 2015 (circular 1441)*. USGS. US Government.

Efroymson, R. A., Langholtz, M. H., Johnson, K., Stokes, B., Brandt, C. C., Davis, M. R., Hellwinckel, C., Kline, K. L., Eaton, L. M., Dunn, J., Canter, C. E., Qin, Z., Cai, H., Wang, M., Scott, D. A., Jager, H. I., Wu, M., Ha, M., Baskaran, L. M., … Dale, V. H. (2017). *2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy, Volume 2: Environmental Sustainability Effects of Select Scenarios from Volume 1 (ORNL/TM-2016/727)*. Oak Ridge National Lab. https://doi.org/10.2172/1340460

EIA. (2020a). *Form EIA-860 detailed data with previous form data (EIA-860A/860B)*. Energy Information Administration. https://www.eia.gov/electricity/data/eia860/

EIA. (2020b). *Form EIA-923 detailed data with previous form data (EIA-906/920)*. Energy Information Administration. https://www.eia.gov/electricity/data/eia923/

EIA. (2020c). *United States—SEDS - U.S. Energy Information Administration (EIA)*. Energy Information Administration. https://www.eia.gov/state/seds/seds-data-complete.php?sid=US

Evenson, E. J., Jones, S. A., Barber, N. L., Barlow, P. M., Blodgett, D. L., Bruce, B. W., Douglas-Mankin, K., Farmer, W. H., Fischer, J. M., Hughes, W. B., Kennen, J., Kiang, J. E., Maupin, M. A., Reeves, H. W., Senay, G. B., Stanton, J. S., Wagner, C. R., & Wilson, J. T. (2018). Continuing progress toward a national assessment of water availability and use. In Continuing progress toward a national assessment of water availability and use (USGS Numbered Series No. 1440; Circular, Vol. 1440). U.S. Geological Survey. https://doi.org/10.3133/cir1440

Finkbeiner, M., & Bach, V. (2021). Life cycle assessment of decarbonization options—Towards scientifically robust carbon neutrality. *The International Journal of Life Cycle Assessment*, *26*, 635–639. https://doi.org/10.1007/s11367-021-01902-4

Finkbeiner, M., Schau, E. M., Lehmann, A., & Traverso, M. (2010). Towards life cycle sustainability assessment. *Sustainability*, *2*(10), 3309–3322. https://doi.org/10.3390/su2103309

Finnveden, G., Hauschild, M. Z., Ekvall, T., Guinee, J., Heijungs, R., Hellweg, S., Koehler, A., Pennington, D., & Suh, S. (2009). Recent developments in life cycle assessment. *Journal of Environmental Management*, *91*(1), 1–21. https://doi.org/10.1016/j.jenvman.2009.06.018

Frischknecht, R., & Rebitzer, G. (2005). The ecoinvent database system: A comprehensive web-based LCA database. *Journal of Cleaner Production*, *13*, 1337–1343. https://doi.org/10.1016/j.jclepro.2005.05.002

Fthenakis, V., & Kim, H. C. (2010). Life-cycle uses of water in U.S. electricity generation. *Renewable and Sustainable Energy Reviews*, *14*(7), 2039–2048. https://doi.org/10.1016/j.rser.2010.03.008

Fyfe, J. C., Derksen, C., Mudryk, L., Flato, G. M., Santer, B. D., Swart, N. C., Molotch, N. P., Zhang, X., Wan, H., Arora, V. K., Scinocca, J., & Jiao, Y. (2017). Large near-term projected snowpack loss over the western United States. *Nature Communications*, *8*(1), 14996. https://doi.org/10.1038/ncomms14996

Gerbens-Leenes, W., Berger, M., & Allan, J. A. (2021). Water footprint and life cycle assessment: The complementary strengths of analyzing global freshwater appropriation and resulting local impacts. *Water*, *13*(6), 803. https://doi.org/10.3390/w13060803

Gernaat, D. E. H. J., de Boer, H. S., Daioglou, V., Yalew, S. G., Müller, C., & van Vuuren, D. P. (2021). Climate change impacts on renewable energy supply. *Nature Climate Change*, *1*, 119–125. https://doi.org/10.1038/s41558-020-00949-9

Gibon, T., Arvesen, A., & Hertwich, E. G. (2017). Life cycle assessment demonstrates environmental co-benefits and trade-offs of low-carbon electricity supply options. *Renewable and Sustainable Energy Reviews*, *76*, 1283–1290. https://doi.org/10.1016/j.rser.2017.03.078

Gleick, P. H. (1994). Water and energy. *Annual Review of Energy and the Environment*, *19*(1), 267–299. https://doi.org/10.1146/annurev.eg.19.110194.001411

Graf, W. L. (1999). Dam nation: A geographic census of American dams and their large-scale hydrologic impacts. *Water Resources Research*, *35*(4), 1305–1311. https://doi.org/10.1029/1999WR900016

Greve, P., Kahil, T., Mochizuki, J., Schinko, T., Satoh, Y., Burek, P., Fischer, G., Tramberend, S., Burtscher, R., Langan, S., & Wada, Y. (2018). Global assessment of water challenges under uncertainty in water scarcity projections. *Nature Sustainability*, *1*(9), 486–494. https://doi.org/10.1038/s41893-018-0134-9

Grubert, E. (2009). Moving towards full renewability: The potential impacts of a renewable hydrogen economy on California's water resource (Undergraduate Engineering Honors Thesis, Stanford University). https://searchworks.stanford.edu/view/dp872vw9896

Grubert, E. (2017a). Implicit prioritization in life cycle assessment: Text mining and detecting metapatterns in the literature. *The International Journal of Life Cycle Assessment*, *22*(2), 148–158. https://doi.org/10.1007/s11367-016-1153-2

Grubert, E. (2017b). The need for a preference-based multicriteria prioritization framework in life cycle sustainability assessment. *Journal of Industrial Ecology*, *21*(6), 1522–1535. https://doi.org/10.1111/jiec.12631

Grubert, E. (2020). Fossil electricity retirement deadlines for a just transition. *Science*, *370*(6521), 1171–1173. https://doi.org/10.1126/science.abe0375

Grubert, E., & Brandt, A. R. (2019). Three considerations for modeling natural gas system methane emissions in life cycle assessment. *Journal of Cleaner Production*, *222*, 760–767. https://doi.org/10.1016/j.jclepro.2019.03.096

Grubert, E., Rogers, E., & Sanders, K. T. (2020). Consistent terminology and reporting are needed to describe water quantity use. *Journal of Water Resources Planning and Management*, *146*(8), 04020064. https://doi.org/10.1061/(ASCE)WR.1943-5452.0001241

Grubert, E., & Sanders, K. T. (2018). Water use in the United States energy system: A National Assessment and unit process inventory of water consumption and withdrawals. *Environmental Science & Technology*, *52*(11), 6695–6703. https://doi.org/10.1021/acs.est.8b00139

Grubert, E., & Webber, M. E. (2017). Synthetic flows for engineered systems with nonstationary parameters: Study of Maui's Wailoa ditch. *Journal of Hydrologic Engineering*, *22*(2), 05016033. https://doi.org/10.1061/(ASCE)HE.1943-5584.0001468

Guinée, J. B., Heijungs, R., Huppes, G., Zamagni, A., Masoni, P., Buonamici, R., Ekvall, T., & Rydberg, T. (2011). Life cycle assessment: Past, present, and future. *Environmental Science & Technology*, *45*(1), 90–96. https://doi.org/10.1021/es101316v

Guinée, J. B., Huppes, G., & Heijungs, R. (2001). Developing an LCA guide for decision support. *Environmental Management and Health*, *12*(3), 301–311. https://doi.org/10.1108/09566160110392416

Hall, J. W., Grey, D., Garrick, D., Fung, F., Brown, C., Dadson, S. J., & Sadoff, C. W. (2014). Coping with the curse of freshwater variability. *Science*, *346*(6208), 429–430. https://doi.org/10.1126/science.1257890

Hamlet, A. F., Mote, P. W., Clark, M. P., & Lettenmaier, D. P. (2005). Effects of temperature and precipitation variability on snowpack trends in the Western United States. *Journal of Climate*, *18*(21), 4545–4561. https://doi.org/10.1175/JCLI3538.1

He, G., Zhao, Y., Jiang, S., Zhu, Y., Li, H., & Wang, L. (2019). Impact of virtual water transfer among electric sub-grids on China's water sustainable developments in 2016, 2030, and 2050. *Journal of Cleaner Production*. *239*, 118056. https://doi.org/10.1016/j.jclepro.2019.118056

Heijungs, R. (1998). Towards eco-efficiency with LCA's prevention principle: An epistemological foundation of LCA using axioms. In J. E. M. Klostermann & A. Tukker (Eds.), *Product innovation and eco-efficiency* (pp. 175–185). Springer.

Heijungs, R., Huppes, G., & Guinée, J. B. (2010). Life cycle assessment and sustainability analysis of products, materials and technologies. Toward a scientific framework for sustainability life cycle analysis. *Polymer Degradation and Stability*, *95*(3), 422–428. https://doi.org/10.1016/j.polymdegradstab.2009.11.010

Hertwich, E. G., Gibon, T., Bouman, E. A., Arvesen, A., Suh, S., Heath, G. A., Bergesen, J. D., Ramirez, A., Vega, M. I., & Shi, L. (2014). Integrated life-cycle assessment of electricity-supply scenarios confirms global environmental benefit of low-carbon technologies. In *Proceedings of the National Academy of Sciences* (201312753). 112(20), 6277–6282. https://doi.org/10.1073/pnas.1312753111

Hill, J., Kern, J. D., Rupp, D., Voisin, N., & Characklis, G. W. (2021). The effects of climate change on interregional electricity market dynamics on the U.S. West Coast. *Earth and Space Science Open Archive ESSOAr*. *9*(7), e2021EF002096. https://doi.org/10.1002/essoar.10506741.1

Hoekstra, A. Y. (2016). A critique on the water-scarcity weighted water footprint in LCA. *Ecological Indicators*, *66*, 564–573. https://doi.org/10.1016/j.ecolind.2016.02.026

Hoekstra, A. Y. (2017). Water footprint assessment: Evolvement of a new research field. *Water Resources Management*, *31*(10), 3061–3081. https://doi.org/10.1007/s11269-017-1618-5

Hoekstra, A. Y., Chapagain, A., Aldaya, M. M., & Mekonnen, M. M. (Eds.). (2011). *The water footprint assessment manual: Setting the global standard*. Earthscan.

Huijbregts, M. A. J., Hellweg, S., Frischknecht, R., Hendriks, H. W. M., Hungerbühler, K., & Hendriks, A. J. (2010). Cumulative energy demand as predictor for the environmental burden of commodity production. *Environmental Science & Technology*, *44*(6), 2189–2196. https://doi.org/10.1021/es902870s

Intergovernmental Panel on Climate Change. (2014). IPCC fifth assessment report. https://www.ipcc.ch/report/ar5/

IPCC (2013). Climate change 2013: The physical science basis. In T. F. Stocker, D. Qin, G.-K. Plattner, M. Tignor, S. K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, & P. M. Midgley (Eds.), *Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press.

ISO. (2014). ISO 14046:2014—Environmental management—Water footprint—Principles, requirements and guidelines. https://www.iso.org/standard/43263.html

Kao, S.-C., Sale, M. J., Ashfaq, M., Uria Martinez, R., Kaiser, D. P., Wei, Y., & Diffenbaugh, N. S. (2015). Projecting changes in annual hydropower generation using regional runoff data: An assessment of the United States federal hydropower plants. *Energy*, *80*, 239–250. https://doi.org/10.1016/j.energy.2014.11.066

Klise, G. T., Tidwell, V. C., Reno, M. D., Moreland, B. D., Zemlick, K. M., & Macknick, J. (2013). Water use and supply concerns for utility-scale solar projects in the southwestern United States. SAND2013-5238. Sandia National Laboratories. http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.490.1952rep=rep1type=pdf

Klos, P. Z., Link, T. E., & Abatzoglou, J. T. (2014). Extent of the rain-snow transition zone in the western U.S. under historic and projected climate. *Geophysical Research Letters*, *41*(13), 4560–4568. https://doi.org/10.1002/2014GL060500

Kounina, A., Margni, M., Bayart, J.-B., Boulay, A.-M., Berger, M., Bulle, C., Frischknecht, R., Koehler, A., Milà i Canals, L., Motoshita, M., Núñez, M., Peters, G., Pfister, S., Ridoutt, B., van Zelm, R., Verones, F., & Humbert, S. (2013). Review of methods addressing freshwater use in life cycle inventory and impact assessment. *The International Journal of Life Cycle Assessment*, *18*(3), 707–721. https://doi.org/10.1007/s11367-012-0519-3

Krakauer, N. Y., & Fung, I. (2008). Mapping and attribution of change in streamflow in the coterminous United States. *Hydrology and Earth System Sciences*, *12*(4), 1111–1120. https://doi.org/10.5194/hess-12-1111-2008

Langbein, W. B. (1959). *Water yield and reservoir storage in the United States*. United States Geological Survey.

Li, D., Wrzesien, M. L., Durand, M., Adam, J., & Lettenmaier, D. P. (2017). How much runoff originates as snow in the western United States, and how will that change in the future? *Geophysical Research Letters*, *44*(12), 6163–6172. https://doi.org/10.1002/2017GL073551

Li, Y., Gao, H., Zhao, G., & Tseng, K.-H. (2020). A high-resolution bathymetry dataset for global reservoirs using multi-source satellite imagery and altimetry. *Remote Sensing of Environment*, *244*, 111831. https://doi.org/10.1016/j.rse.2020.111831

Lin, C.-C., & Chiueh, P.-T. (2021). Mapping the local impacts of water consumption with regionalized three-dimensional arrays. *The International Journal of Life Cycle Assessment*, *26*, 1495–1504. https://doi.org/10.1007/s11367-021-01886-1

Lins, H. F. (2012). *USGS Hydro-Climatic Data Network 2009 (HCDN-2009) (USGS Numbered Series No. 2012–3047; Fact Sheet, Vols. 2012–3047)*. U.S. Geological Survey. https://doi.org/10.3133/fs20123047

Lins, H. F., & Slack, J. R. (1999). Streamflow trends in the United States. *Geophysical Research Letters*, *26*(2), 227–230. https://doi.org/10.1029/1998GL900291

Logan, L. H., Gupta, R. S., Ando, A., Suski, C., & Stillwell, A. S. (2021). Quantifying tradeoffs between electricity generation and fish populations via population habitat duration curves. *Ecological Modelling*, *440*, 109373. https://doi.org/10.1016/j.ecolmodel.2020.109373

Lubega, W. N., & Stillwell, A. S. (2017). Maintaining electric grid reliability under hydrologic drought and heat wave conditions. *Applied Energy*, *210*, 538–549. https://doi.org/10.1016/j.apenergy.2017.06.091

Luce, C. H., & Holden, Z. A. (2009). Declining annual streamflow distributions in the Pacific Northwest United States, 1948–2006. *Geophysical Research Letters*, *36*(16). https://doi.org/10.1029/2009GL039407

Lucey, J. T. D., Reager, J. T., & Lopez, S. R. (2020). Global partitioning of runoff generation mechanisms using remote sensing data. *Hydrology and Earth System Sciences*, *24*(3), 1415–1427. https://doi.org/10.5194/hess-24-1415-2020

Macknick, J., Newmark, R., Heath, G., & Hallett, K. C. (2012). Operational water consumption and withdrawal factors for electricity generating technologies: A review of existing literature. *Environmental Research Letters*, *7*(4), 045802. https://doi.org/10.1088/1748-9326/7/4/045802

Macknick, J., Sattler, S., Averyt, K., Clemmer, S., & Rogers, J. (2012). The water implications of generating electricity: Water use across the United States based on different electricity pathways through 2050. *Environmental Research Letters*, *7*(4), 045803. https://doi.org/10.1088/1748-9326/7/4/045803

Madakumbura, G. D., Thackeray, C. W., Norris, J., Goldenson, N., & Hall, A. (2021). Anthropogenic influence on extreme precipitation over global land areas seen in multiple observational datasets. *Nature Communications*, *12*(1), 3944. https://doi.org/10.1038/s41467-021-24262-x

Mankin, J. S., & Diffenbaugh, N. S. (2015). Influence of temperature and precipitation variability on near-term snow trends. *Climate Dynamics*, *45*(3), 1099–1116. https://doi.org/10.1007/s00382-014-2357-4

Marshall, A. M., Abatzoglou, J. T., Link, T. E., & Tennant, C. J. (2019). Projected changes in interannual variability of peak snowpack amount and timing in the Western United States. *Geophysical Research Letters*, *46*(15), 8882–8892. https://doi.org/10.1029/2019GL083770

Marshall, A. M., & Grubert, E. (2021). Hydroelectricity modeling for low-carbon and no-carbon grids: Empirical constraints for optimization and dispatch models. *Review at Energy and Environmental Science*.

Marston, L., Ao, Y., Konar, M., Mekonnen, M. M., & Hoekstra, A. Y. (2018). High-resolution water footprints of production of the United States. *Water Resources Research*, *54*, 2288–2316. https://doi.org/10.1002/2017WR021923

Maupin, M., Kenny, J., Hutson, S., Lovelace, J., Barber, N., & Linsey, K. (2014). *Estimated use of water in the United States in 2010 (Circular No. 1405)*. USGS.

McDonald, R. I., Weber, K., Padowski, J., Flörke, M., Schneider, C., Green, P. A., Gleeson, T., Eckman, S., Lehner, B., Balk, D., Boucher, T., Grill, G., & Montgomery, M. (2014). Water on an urban planet: Urbanization and the reach of urban water infrastructure. *Global Environmental Change*, *27*, 96–105. https://doi.org/10.1016/j.gloenvcha.2014.04.022

McManamay, R. A., Kc, B., Allen-Dumas, M. R., Kao, S.-C., Brelsford, C. M., Ruddell, B. L., Sanyal, J., Stewart, R. N., & Bhaduri, B. L. (2021). Reanalysis of water withdrawal for irrigation, electric power, and public supply sectors in the conterminous United States, 1950–2016. *Water Resources Research*, *57*(2), e2020WR027751. https://doi.org/10.1029/2020WR027751

McManamay, R. A., Oigbokie, C. O., Kao, S.-C., & Bevelhimer, M. S. (2016). Classification of US hydropower dams by their modes of operation. *River Research and Applications*, *32*(7), 1450–1468. https://doi.org/10.1002/rra.3004

Mekonnen, M., Gerbens-Leenes, P., & Hoekstra, A. (2015). The consumptive water footprint of electricity and heat: A global assessment. *Environmental Science: Water Research & Technology*, *1*(3), 285–297. https://doi.org/10.1039/C5EW00026B

Meldrum, J., Nettles-Anderson, S., Heath, G., & Macknick, J. (2013). Life cycle water use for electricity generation: A review and harmonization of literature estimates. *Environmental Research Letters*, *8*(1), 015031. https://doi.org/10.1088/1748-9326/8/1/015031

Meron, N., Blass, V., Garb, Y., Kahane, Y., & Thoma, G. (2016). Why going beyond standard LCI databases is important: Lessons from a meta-analysis of potable water supply system LCAs. *The International Journal of Life Cycle Assessment*, *21*(8), 1134–1147. https://doi.org/10.1007/s11367-016-1096-7

Meshel, T. (2018). Environmental justice in the United States: The human right to water. *Washington Journal of Environmental Law and Policy*, *8*(2), 264–297.

Miara, A., Cohen, S. M., Macknick, J., Vörösmarty, C. J., Corsi, F., Sun, Y., Tidwell, V. C., Newmark, R., & Fekete, B. M. (2019). Climate-water adaptation for future US electricity infrastructure. *Environmental Science & Technology.*, *53*, 14029–14040. https://doi.org/10.1021/acs.est.9b03037

Miara, A., Macknick, J. E., Vörösmarty, C. J., Tidwell, V. C., Newmark, R., & Fekete, B. (2017). Climate and water resource change impacts and adaptation potential for US power supply. *Nature Climate Change*, *7*(11), 793–798. https://doi.org/10.1038/nclimate3417

Milly, P. C. D., Betancourt, J., Falkenmark, M., Hirsch, R. M., Kundzewicz, Z. W., Lettenmaier, D. P., & Stouffer, R. J. (2008). Stationarity is dead: Whither water management? *Science*, *319*(5863), 573–574. https://doi.org/10.1126/science.1151915

Mote, P. W., Li, S., Lettenmaier, D. P., Xiao, M., & Engel, R. (2018). Dramatic declines in snowpack in the western US. *npj Climate and Atmospheric Science*, *1*(1), 1–6. https://doi.org/10.1038/s41612-018-0012-1

Mulvaney, D. (2017). Identifying the roots of Green civil war over utility-scale solar energy projects on public lands across the American southwest. *Journal of Land Use Science*, *12*(6), 493–515. https://doi.org/10.1080/1747423X.2017.1379566

Nature Sustainability Editorial Board. (2021). Too much and not enough. *Nature Sustainability*, *4*(8), 659–659. https://doi.org/10.1038/s41893-021-00766-8

NCA. (2018). *Fourth National Climate Assessment* (pp. 1–470). U.S. Global Change Research Program. https://nca2018.globalchange.govhttps://nca2018.globalchange.gov/chapter/2

Nicot, J.-P., & Scanlon, B. R. (2012). Water use for shale-gas production in Texas, U.S. *Environmental Science & Technology*, *46*(6), 3580–3586. https://doi.org/10.1021/es204602t

Nijssen, B., O'Donnell, G. M., Hamlet, A. F., & Lettenmaier, D. P. (2001). Hydrologic sensitivity of global rivers to climate change. *Climatic Change*, *50*(1), 143–175. https://doi.org/10.1023/A:1010616428763

O'Gorman, P. A., & Schneider, T. (2009). The physical basis for increases in precipitation extremes in simulations of 21st-century climate change. *Proceedings of the National Academy of Sciences*, *106*(35), 14773–14777. https://doi.org/10.1073/pnas.0907610106

Owens, J. W. (1997). Life-cycle assessment: Constraints on moving from inventory to impact assessment. *Journal of Industrial Ecology*, *1*(1), 37–49. https://doi.org/10.1162/jiec.1997.1.1.37

Padowski, J. C., & Gorelick, S. M. (2014). Global analysis of urban surface water supply vulnerability. *Environmental Research Letters*, *9*(10), 104004. https://doi.org/10.1088/1748-9326/9/10/104004

Padowski, J. C., & Jawitz, J. W. (2012). Water availability and vulnerability of 225 large cities in the United States. *Water Resources Research*, *48*(12). https://doi.org/10.1029/2012WR012335

Paltán, H. A., Pant, R., Plummer Braeckman, J., & Dadson, S. J. (2021). Increased water risks to global hydropower in 1.5 °C and 2.0 °C warmer worlds. *Journal of Hydrology*, *599*, 126503. https://doi.org/10.1016/j.jhydrol.2021.126503

Patrizio, P., Pratama, Y. W., & Dowell, N. M. (2020). Socially equitable energy system transitions. *Joule*, *4*(8), 1700–1713. https://doi.org/10.1016/j.joule.2020.07.010

Payne, J. T., Wood, A. W., Hamlet, A. F., Palmer, R. N., & Lettenmaier, D. P. (2004). Mitigating the effects of climate change on the water resources of the Columbia River basin. *Climatic Change*, *62*(1), 233–256. https://doi.org/10.1023/B:CLIM.0000013694.18154.d6

Peer, R. A. M., Grubert, E., & Sanders, K. T. (2019). A regional assessment of the water embedded in the US electricity system. *Environmental Research Letters*, *14*(8), 084014. https://doi.org/10.1088/1748-9326/ab2daa

Peer, R. A. M., & Sanders, K. T. (2016). Characterizing cooling water source and usage patterns across US thermoelectric power plants: A comprehensive assessment of self-reported cooling water data. *Environmental Research Letters*, *11*(12), 124030. https://doi.org/10.1088/1748-9326/aa51d8

Peer, R. A. M., & Sanders, K. T. (2018). The water consequences of a transitioning US power sector. *Applied Energy*, *210*, 613–622. https://doi.org/10.1016/j.apenergy.2017.08.021

Perrone, D., Hornberger, G., van Vliet, O., & van der Velde, M. (2015). A review of the United States' past and projected water use. *JAWRA Journal of the American Water Resources Association*, *51*(5), 1183–1191. https://doi.org/10.1111/1752-1688.12301

Persad, G. G., Swain, D. L., Kouba, C., & Ortiz-Partida, J. P. (2020). Inter-model agreement on projected shifts in California hydroclimate characteristics critical to water management. *Climatic Change*, *162*, 1493–1513. https://doi.org/10.1007/s10584-020-02882-4

Pfister, S., Boulay, A.-M., Berger, M., Hadjikakou, M., Motoshita, M., Hess, T., Ridoutt, B., Weinzettel, J., Scherer, L., Döll, P., Manzardo, A., Núñez, M., Verones, F., Humbert, S., Buxmann, K., Harding, K., Benini, L., Oki, T., Finkbeiner, M., & Henderson, A. (2017). Understanding the LCA and ISO water footprint: A response to Hoekstra (2016) "A critique on the water-scarcity weighted water footprint in LCA". *Ecological Indicators*, *72*, 352–359. https://doi.org/10.1016/j.ecolind.2016.07.051

Pfister, S., Koehler, A., & Hellweg, S. (2009). Assessing the environmental impacts of freshwater consumption in LCA. *Environmental Science & Technology*, *43*(11), 4098–4104. https://doi.org/10.1021/es802423e

Pfister, S., Saner, D., & Koehler, A. (2011). The environmental relevance of freshwater consumption in global power production. *The International Journal of Life Cycle Assessment*, *16*(6), 580–591. https://doi.org/10.1007/s11367-011-0284-8

Pfister, S., Scherer, L., & Buxmann, K. (2020). Water scarcity footprint of hydropower based on a seasonal approach—Global assessment with sensitivities of model assumptions tested on specific cases. *Science of the Total Environment*, *724*, 138188. https://doi.org/10.1016/j.scitotenv.2020.138188

Pfister, S., & Suh, S. (2015). Environmental impacts of thermal emissions to freshwater: Spatially explicit fate and effect modeling for life cycle assessment and water footprinting. *The International Journal of Life Cycle Assessment*, *1*, 927–936. https://doi.org/10.1007/s11367-015-0893-8

Pfister, S., Vionnet, S., Levova, T., & Humbert, S. (2016). Ecoinvent 3: Assessing water use in LCA and facilitating water footprinting. *The International Journal of Life Cycle Assessment*, *21*(9), 1349–1360. https://doi.org/10.1007/s11367-015-0937-0

Pinsonnault, A., Lesage, P., Levasseur, A., & Samson, R. (2014). Temporal differentiation of background systems in LCA: Relevance of adding temporal information in LCI databases. *The International Journal of Life Cycle Assessment*, *19*(11), 1843–1853. https://doi.org/10.1007/s11367-014-0783-5

Prein, A. F., Rasmussen, R. M., Ikeda, K., Liu, C., Clark, M. P., & Holland, G. J. (2017). The future intensification of hourly precipitation extremes. *Nature Climate Change*, *7*(1), 48–52. https://doi.org/10.1038/nclimate3168

Raptis, C. E., Boucher, J. M., & Pfister, S. (2017). Assessing the environmental impacts of freshwater thermal pollution from global power generation in LCA. *Science of the Total Environment*, *580*, 1014–1026. https://doi.org/10.1016/j.scitotenv.2016.12.056

Raptis, C. E., Oberschelp, C., & Pfister, S. (2020). The greenhouse gas emissions, water consumption, and heat emissions of global steam-electric power production: A generating unit level analysis and database. *Environmental Research Letters*, *15*(10), 104029. https://doi.org/10.1088/1748-9326/aba6ac

Richter, B., & Thomas, G. (2007). Restoring environmental flows by modifying dam operations. *Ecology and Society*, *12*(1). https://doi.org/10.5751/ES-02014-120112

Rupp, D. E., Chegwidden, O. S., Nijssen, B., & Clark, M. P. (2021). Changing river network synchrony modulates projected increases in high flows. *Water Resources Research*, *57*(4), e2020WR028713. https://doi.org/10.1029/2020WR028713

Sattler, S., Macknick, J., Yates, D., Flores-Lopez, F., Lopez, A., & Rogers, J. (2012). Linking electricity and water models to assess electricity choices at water-relevant scales. *Environmental Research Letters*, *7*(4), 045804. https://doi.org/10.1088/1748-9326/7/4/045804

Sauquet, E., Shanafield, M., Hammond, J. C., Sefton, C., Leigh, C., & Datry, T. (2021). Classification and trends in intermittent river flow regimes in Australia, northwestern Europe and USA: A global perspective. *Journal of Hydrology*, *597*, 126170. https://doi.org/10.1016/j.jhydrol.2021.126170

Scanlon, B. R., Reedy, R. C., & Nicot, J.-P. (2014). Comparison of water use for hydraulic fracturing for unconventional oil and gas versus conventional oil. *Environmental Science & Technology*, *48*(20), 12386–12393. https://doi.org/10.1021/es502506v

Scherer, L., & Pfister, S. (2016). Global water footprint assessment of hydropower. *Renewable Energy*, *99*, 711–720. https://doi.org/10.1016/j.renene.2016.07.021

Seidel, C. (2016). The application of life cycle assessment to public policy development. *The International Journal of Life Cycle Assessment*, *21*, 337–348. https://doi.org/10.1007/s11367-015-1024-2

Siddik, M. A. B., Chini, C. M., & Marston, L. (2020). Water and carbon footprints of electricity are sensitive to geographical attribution methods. *Environmental Science & Technology*, *54*(12), 7533–7541. https://doi.org/10.1021/acs.est.0c00176

Solley, W. B., & US Geological Survey. (1998). *Estimated use of water in the United States in 1995*. U.S. Geological Survey, Branch of Information Services.

Spang, E. S., Moomaw, W. R., Gallagher, K. S., Kirshen, P. H., & Marks, D. H. (2014). The water consumption of energy production: An international comparison. *Environmental Research Letters*, *9*(10), 105002. https://doi.org/10.1088/1748-9326/9/10/105002

Sproat, K. (2011). Wai through Kanawai: Water for Hawaii's streams and justice for Hawaiian communities symposium—Changing conceptions of water in the law. *Marquette Law Review*, *95*(1), 127–212.

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2004). Changes in snowmelt runoff timing in Western North America under a "business as usual" climate change scenario. *Climatic Change*, *62*(1), 217–232. https://doi.org/10.1023/B:CLIM.0000013702.22656.e8

Stewart, I. T., Cayan, D. R., & Dettinger, M. D. (2005). Changes toward earlier streamflow timing across Western North America. *Journal of Climate*, *18*(8), 1136–1155. https://doi.org/10.1175/JCLI3321.1

Swain, D. L., Langenbrunner, B., Neelin, J. D., & Hall, A. (2018). Increasing precipitation volatility in twenty-first-century California. *Nature Climate Change*, *8*(5), 427–433. https://doi.org/10.1038/s41558-018-0140-y

Szinai, J. K., Deshmukh, R., Kammen, D. M., & Jones, A. D. (2020). Evaluating cross-sectoral impacts of climate change and adaptations on the energy-water nexus: A framework and California case study. *Environmental Research Letters*, *15*(12), 124065. https://doi.org/10.1088/1748-9326/abc378

Tarroja, B., Forrest, K., Chiang, F., AghaKouchak, A., & Samuelsen, S. (2019). Implications of hydropower variability from climate change for a future, highly-renewable electric grid in California. *Applied Energy*, *237*, 353–366. https://doi.org/10.1016/j.apenergy.2018.12.079

Tarroja, B., Peer, R. A. M., Sanders, K. T., & Grubert, E. (2020). How do non-carbon priorities affect zero-carbon electricity systems? A case study of freshwater consumption and cost for senate bill 100 compliance in California. *Applied Energy*, *265*, 114824. https://doi.org/10.1016/j.apenergy.2020.114824

Tong, D., Zhang, Q., Zheng, Y., Caldeira, K., Shearer, C., Hong, C., Qin, Y., & Davis, S. J. (2019). Committed emissions from existing energy infrastructure jeopardize 1.5 °C climate target. *Nature*, *572*(7769), 373–377. https://doi.org/10.1038/s41586-019-1364-3

US DOE. (1980). *Technology characterizations: Environmental information handbook (DOE/EV-0072)*. US Department of Energy.

US DOE. (2006). *Energy demands on water resources: Report to congress on the interdependency of energy and water*. US Department of Energy. https://www.sciencebase.gov/catalog/item/5140abbbe4b089809dbf533c

Vaca-Jiménez, S., Gerbens-Leenes, P. W., Nonhebel, S., & Hubacek, K. (2021). Unreflective use of old data sources produced echo chambers in the water–electricity nexus. *Nature Sustainability*, *1*, 537–546. https://doi.org/10.1038/s41893-021-00686-7

van Vliet, M. T. H., Sheffield, J., Wiberg, D., & Wood, E. F. (2016). Impacts of recent drought and warm years on water resources and electricity supply worldwide. *Environmental Research Letters*, *11*(12), 124021. https://doi.org/10.1088/1748-9326/11/12/124021

van Vliet, M. T. H., Wiberg, D., Leduc, S., & Riahi, K. (2016). Power-generation system vulnerability and adaptation to changes in climate and water resources. *Nature Climate Change*, *6*(4), 375–380. https://doi.org/10.1038/nclimate2903

Voisin, N., Dyreson, A., Fu, T., O'Connell, M., Turner, S. W. D., Zhou, T., & Macknick, J. (2020). Impact of climate change on water availability and its propagation through the Western U.S. power grid. *Applied Energy*, *276*, 115467. https://doi.org/10.1016/j.apenergy.2020.115467

Vorosmarty, C. J. (2000). Global water resources: Vulnerability from climate change and population growth. *Science*, *289*(5477), 284–288. https://doi.org/10.1126/science.289.5477.284

Wang, J., Yu, Z., Zeng, X., Wang, Y., Li, K., & Deng, S. (2021). Water-energy-carbon nexus: A life cycle assessment of post-combustion carbon capture technology from power plant level. *Journal of Cleaner Production*, *312*, 127727. https://doi.org/10.1016/j.jclepro.2021.127727

Ween, G. B., & Colombi, B. J. (2013). Two Rivers: The politics of wild Salmon, indigenous rights and natural resource management. *Sustainability*, *5*(2), 478–495. https://doi.org/10.3390/su5020478

Williams, J. H., Jones, R. A., Haley, B., Kwok, G., Hargreaves, J., Farbes, J., & Torn, M. S. (2021). Carbon-neutral pathways for the United States. *AGU Advances*, *2*(1), e2020AV000284. https://doi.org/10.1029/2020AV000284

Wilson, N. J., Montoya, T., Arseneault, R., & Curley, A. (2021). Governing water insecurity: Navigating indigenous water rights and regulatory politics in settler colonial states. *Water International*, *1*, 1–19. https://doi.org/10.1080/02508060.2021.1928972

Wu, M., Zhang, Z., & Chiu, Y. (2014). Life-cycle water quantity and water quality implications of biofuels. *Current Sustainable/Renewable Energy Reports*, *1*(1), 3–10. https://doi.org/10.1007/s40518-013-0001-2

Young, P. S., Cech, J. J., & Thompson, L. C. (2011). Hydropower-related pulsed-flow impacts on stream fishes: A brief review, conceptual model, knowledge gaps, and research needs. *Reviews in Fish Biology and Fisheries*, *21*(4), 713–731. https://doi.org/10.1007/s11160-011-9211-0

Zacarias, L. M., & Grubert, E. (2021). Effects of implausible power plant lifetime assumptions on US federal energy system projected costs, greenhouse gas emissions, air pollution, and water use. *Environmental Research: Infrastructure and Sustainability*, *1*. https://doi.org/10.1088/2634-4505/abff0c

Zou, Z., Xiao, X., Dong, J., Qin, Y., Doughty, R. B., Menarguez, M. A., Zhang, G., & Wang, J. (2018). Divergent trends of open-surface water body area in the contiguous United States from 1984 to 2016. *Proceedings of the National Academy of Sciences*, *115*(15), 3810–3815. https://doi.org/10.1073/pnas.1719275115

How to cite this article: Grubert, E., & Marshall, A. (2022). Water for energy: Characterizing co-evolving energy and water systems under twin climate and energy system nonstationarities. *Wiley Interdisciplinary Reviews: Water*, e1576. https://doi.org/10.1002/wat2.1576