The Water Footprint of California's Energy System, 1990-2012

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Abstract

California's energy and water systems are interconnected and have evolved in recent decades in response to changing conditions and policy goals. For this analysis, we use a water footprint methodology to examine water requirements of energy products consumed in California between 1990 and 2012. We combine energy production, trade, and consumption data with estimates of the blue and green water footprints of energy products. We find that while California's total annual energy consumption increased by just 2.6% during the analysis period, the amount of water required to produce that energy grew by 260%. Nearly all of the increase in California's energy-related water footprint was associated with water use in locations outside of California, where energy products that the state consumes were, and continue to be, produced. We discuss these trends and the implications for California's future energy system as it relates to climate change and expected water management challenges inside and outside the state. Our analysis shows that while California's energy policies have supported climate mitigation efforts, they have increased vulnerability to climate impacts, especially greater hydrologic uncertainty. More integrated analysis and planning are needed to ensure that climate adaptation and mitigation strategies do not work at cross purposes.

Keywords: water footprint; California's energy system; biofuel; climate

Introduction

Water and energy systems are interdependent across spatial and temporal scales, and the term "energy-water nexus" has been used to draw attention to these connections.[1–4] Water and sewerage systems, for example, use large amounts of energy for pumping, storage, treatment, and usage of water, accounting for about 13% of national electricity usage in the United States.[5] Energy systems, in turn, use and pollute large volumes of water for hydropower generation, extraction and processing of fuels, energy transformation, and end uses.[6] While these processes can have more immediate, regional impacts,[7–9] they can also have longer term global impacts, as greenhouse gas emissions from energy systems drive shifts in the global hydrologic cycle.[10–12]

Given these interdependencies as well as constraints on both water and energy supplies, energy and water policies that do not balance demands and impacts across resource categories risk shifting adverse impacts geographically and temporally rather than alleviating them. Here we focus on water impacts of energy systems. Energy policies are increasingly driven by the need to curtail anthropogenic greenhouse gas emissions in light of well-documented atmospheric limits and expected climate impacts. Despite growing recognition of the "global water crisis"[13,14] and the potential for climate change to exacerbate these concerns,[15–17] policy- and decision-makers have often failed to consider the implications of energy policies on water resources. Thus, a motivating question that this paper seeks to address is whether and how energy policies intended to mitigate climate change can simultaneously allow energy systems to adapt to climate impacts, especially hydrologic uncertainty. Specifically, we examine the case of California's energy system from 1990-2012 to understand how energy policies have affected demands on water resources and provide insight into the impacts of climate mitigation policies.

California's energy system has faced real and perceived constraints based on the availability of water resources. Most directly, seasonal precipitation and snowpack in the Sierra Nevada mountain range determines the state's hydropower generation, which provides an average of about 15% of in-state electricity generation. During drought years, hydropower generation is curtailed, forcing the state's grid operator to generate electricity from other in-state resources or import more electricity from other states to meet demand. This trend was apparent most recently in 2012 and 2013, as well as in 2014, the worst drought year on record.[18] Similarly, some groups have called for a ban on further development of California's shale oil resources using hydraulic fracturing and other well stimulation techniques due to the drought and other water supply constraints.[19]

Over the past several decades, California has emerged as a leader in energy efficiency, renewable energy generation, and greenhouse gas (GHG) management. 1990, as the benchmark for the state's GHG inventory, represents a logical starting year for our analysis. By 2012, California's total energy use was only 2.6% higher than in 1990,[20] and the state's GHG inventory for energy was below 1990 levels.[21,22] Meanwhile, the state's population increased by 27%, and gross domestic product grew by 68% (Figure 1).[23] These energy achievements were primarily made through aggressive greenhouse gas management policies, including a low carbon fuel standard, a renewables portfolio standard for electric utilities, and, most recently, a cap and trade program.[24] Energy efficiency programs, demographic changes, prices, and consumer preferences have also played a role in shaping California's energy landscape.[25] Each of these changes has resulted in shifts in the amount and type of fuel use as well as in production technologies and locations.

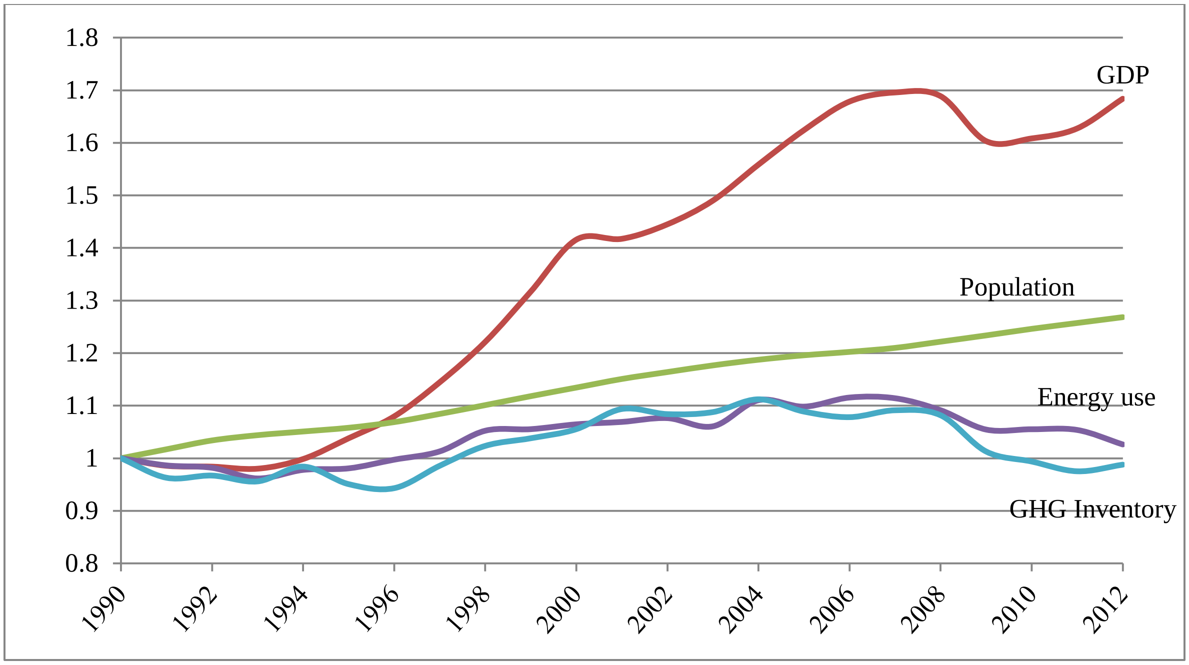

Figure 1: Changes in California GDP, Population, Energy Use, and Energy Greenhouse Gas Inventory from 1990 to 2012.[20–23]

Energy and other policies can be aided by analytical tools to describe and provide decision-making frameworks on complex interactions between social systems and energy, water, and other environmental systems.[26–29] In this article, we use a water footprint approach to highlight three features of California's energy-related water footprint (EWF), including (1) the *intensity*, or volume of water consumptively used for the state's energy system; (2) the *type* of water consumed, i.e., blue or green water; and (3), the *location* where the water consumption occurred, i.e., inside or outside of California. Each of these pertains to specific water resource impacts and risks in locations where the energy activities occur. While we do not quantitatively characterize these impacts or the associated risks to California's energy system, we identify how future energy planning might do these analyses.

Interest in the energy-water nexus has increased in recent years, although studies on water uses of energy systems date back at least three decades. Harte and El-Gasseir (1978)[30] assessed regional hydrologic constraints on U.S. electric power generation. Gleick (1994)[31] provided one of the most-cited in-depth studies on water intensity (on a gallons per unit energy basis) of various energy sources, including hydropower, for the entire fuel cycle. Review studies of the water intensity of various fuel sources have also been published.[32–34] While these early efforts focused primarily on electricity sourcing and generation, later research expanded into the areas of transportation fuels, including unconventional fuels and biofuels. King & Webber (2008)[35] analyzed the water intensity across the full fuel cycle for a set of transportation fuels on a gallons-per-mile basis and calculated water demand scenarios based on national energy projections.[36] Fingerman et al (2010)[37] identified regional water considerations in bioethanol production, while Scown et al (2011)[38] included several additional fuel sources, including electricity, to compare stress-weighted upstream water impacts in the U.S..

More recent research has taken a systems approach to assessing how water demands for energy are distributed within and among regions, and with consideration for supply chain impacts. Input-output (I-O) approaches figure prominently in the broader water footprint literature,[39–45] though there have been fewer applications to water-energy nexus studies in particular. Scown et al (2011) based their study on a U.S. economy-wide I-O framework. Zhang and Anadon (2013)[46] used China's linked, province-level I-O tables to trace interregional and intersectoral demands on water resources, and related those demands to human, ecosystem and resource impacts at the watershed scale using a life cycle impact assessment method.

Our analysis differs from previous energy-water nexus studies in three ways. First, by focusing on California, we are able to identify the water implications of a specific set of energy policies. Second, we examine these implications using panel data, allowing trends to provide insights that may be missed in a snapshot analysis. Third, we bring together previous studies that have looked at the water footprint of discrete segments of energy systems, to present a comprehensive understanding of the water footprint of California's total energy system. We expect these attributes of our study to be informative for current and future energy-water decision making and energy policy discussions.

Materials and Methods

We define California's energy system as the full range of energy products consumed within the state's borders, including electricity and direct use of fuels for the household, industrial, commercial and transportation sectors. Energy products make use of multiple energy carriers – natural gas, coal, nuclear fuel, hydropower, geothermal, biomass, wind, and solar – through a range of extraction, processing, refining, and electricity generation activities. While all of these activities take place to varying extents within the state's borders, California also depends on imports of energy products (in one form or another) from neighbors and distant trading partners. Furthermore, energy products within the state are somewhat fungible between different end uses, e.g. natural gas or electric-powered vehicles. The above-mentioned factors make evaluating California's energy system, and the effects of policy on it, complex.

California's energy system underwent significant changes between 1990 and 2012, making it an important time period to study, but also complicating data collection efforts. To account for these complex and dynamic energy patterns, we utilized the framework of the California Energy Balance (CALEB) database, maintained by Lawrence Berkeley National Laboratories.[47] CALEB contains highly disaggregated data on annual energy supply, transformation, and end-use consumption for 30 distinct energy products, from 1990 to 2008. Figure 2 shows a sample Sankey diagram produced by CALEB for 2008, represented in million British thermal units of energy (BTUs). We used data in physical units (barrels of oil, million cubic feet of natural gas, etc.) from CALEB to quantify energy product flows over time. Following methods in de la Rue du Can (2013),[47] we updated physical unit statistics for years 2009 – 2012. To identify the origin and type of imported energy products, we used data from the California Energy Commission on electricity[48] and natural gas,[49] and from the Energy Information Administration on oil, and ethanol.[50] More information on these energy flows can be found in the Supporting Information.

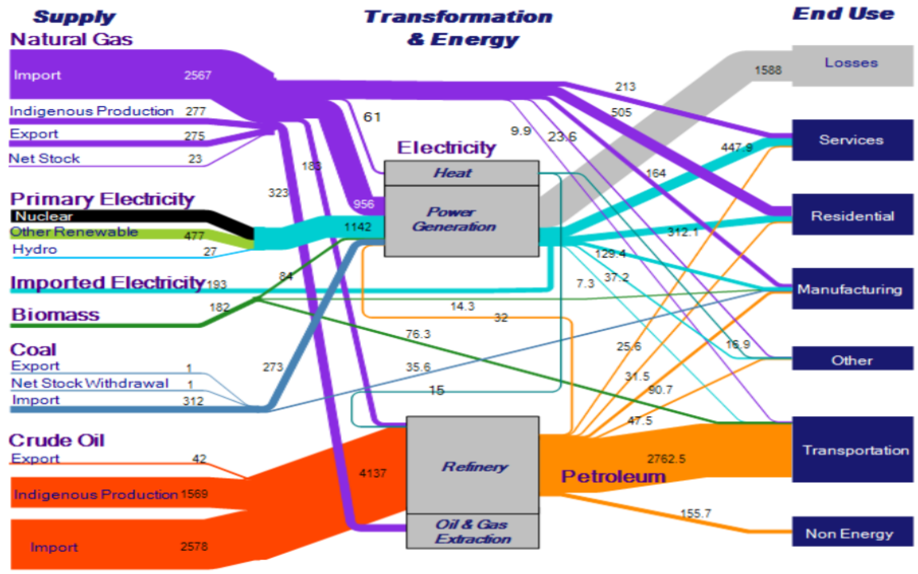

Figure 2: 2008 California energy flows in million BTUs, as shown in De la Rue du Can et al (2013).[47]

Nearly every stage in the production of energy products consumes water, whether through evaporation, contamination, or other ways in which water is unavailable for reuse in the same river basin.[51] We characterize the EWF of an energy product by its "blue" and "green" components: the blue water footprint (blue EWF) of an energy product refers to the consumption of surface or ground water, such as evaporation of water for power plant cooling; the green water footprint (green EWF) refers to the consumption of precipitation and in-situ soil moisture, such as through transpiration from the production of bioenergy feedstocks.[52] The related "grey" water footprint, i.e., the volume of water to assimilate pollutants into water bodies at levels that meet governing standards, is not addressed explicitly in this analysis due to lack of data, although we describe water quality in the discussion section.

Blue EWF factors for energy extraction, processing, and electricity generation were derived from several sources and are shown in Table 1. Meldrum et al (2013)[53] recently completed a review and harmonization of life cycle water use factors on various electricity fuel cycle and generation technologies. We used reported median consumptive use factors for natural gas, coal, nuclear, solar, wind, and geothermal power. We used a related study from the National Renewable Energy Laboratory for consumptive use factors for biomass and hydropower.[34] All these factors were further weighted for the composition of California's electricity consumption when different types of fuel cycle, generation, and cooling technologies could be identified by location and year. Table 2 shows blue and green EWF factors used for extraction, processing and refining of liquid fuels. Consumptive water use factors for oil products were taken from Wu et al. (2011).[54] For bioethanol production, we used country-level weighted average factors from Mekonnen and Hoekstra (2010),[55] including refining and on-farm green and blue water requirements of bioethanol feedstocks. Further details on calculation steps for EWF factors can be found in the Supporting Information.

Table 1: Factors used to calculate California's blue EWF for electricity.

Fuel	Location	Fuel Cycle (l water/MWh)	Generation (l water/MWh)	Source
Coal	All	96	1,895	53
Natural Gas	All	24*	737	53
Nuclear	All	212	1,817	53
Conventional Hydropower	All	17,000†	-	34
Geothermal	All	-	2,265	53
Biomass	All	-	2,090	34
Solar PV	All	-	329	53
Solar Thermal	All	-	3,975	53
Wind	All	-	4	53
Unspecified Imported Electricity	All	1,291	1,399	53

Note: EWF factors are weighted by extraction, processing, and electricity generation technologies pertaining to California's energy system. See Supporting Information for further details.

* The equivalent factor for direct use of natural gas is 0.13 l water/m^3 gas.

† This quantity refers to evaporative losses from reservoirs, which often serve other uses such as storage for flood control, urban and agricultural water supply, and recreation. However, as no methodology exists to accurately allocate consumption among the various uses, we used existing assumptions in the literature that all evaporative losses are attributable to electricity production.[34]

Table 2: Factors used to calculate California's blue and green EWF for liquid fuels.

Fuel	Location	Extraction/Farming (l water/l fuel)		Refining (l water/l fuel)	Source
		Green Water	Blue Water		
Crude Oil	Alaska & California	n/a	5.4	1.5	54
Crude Oil	Foreign Countries	n/a	3.0	1.5	54
Ethanol	California	n/a	n/a	3	54
Ethanol	USA (Corn)	1,220	148	3	55
Ethanol	Brazil (Sugar)	1,224	54	3	55
Ethanol	Canada (Corn)	1,149	13	3	55
Ethanol	China (Corn)	1,848	172	3	55
Ethanol	Costa Rica (Sugar)	1,404	245	3	55
Ethanol	El Salvador (Sugar)	1,476	54	3	55
Ethanol	Guatemala (Sugar)	1,283	127	3	55
Ethanol	Jamaica (Sugar)	2,085	271	3	55
Ethanol	Nicaragua (Sugar)	1,459	161	3	55
Ethanol	Trinidad & Tobago (Sugar)	2,223	78	3	55
Ethanol	Other (Sugar)	1,400	575	3	55

Blue and green EWF factors (e.g. liters of water per liter of ethanol) were multiplied by physical units of energy consumed in California (e.g., liters of ethanol) for each year between 1990 and 2012. This method assumed that blue and green EWF factors did not change over the 23-year time frame. In reality, we expect that many of these factors likely have decreased due to efficiency improvements, weather, etc. Many of these factors were derived with data from around the middle of our time series (2000) but we lack data with which to model changes before and after these points. Thus, results are indicative of how California's EWF has changed with respect to changes in its energy system. Further research into how consumptive water use factors have changed in the energy sector could further enrich this approach and subsequent findings.

Results

The amount of water required to support California's total energy system has changed significantly over the time period examined (Figure 3a). In 1990, the state's total EWF was about 2.1 cubic kilometers (km^3) while in 2012, it was 7.7 km^3, representing more than a three-fold increase. Much of the increase is attributable to water consumed for ethanol production, which increased from 0.2 km^3 in 1990 to 6.3 km^3 in 2012. Indeed, California's EWF is highly sensitive to the role of ethanol (given our methods and assumptions) and we discuss this role at greater length below, after examining the EWF of other energy sources.

The EWF of California's natural gas consumption for the residential, commercial, industrial, and electric power sectors increased from 0.005 km^3 in 1990 to 0.013 km^3 in 2012, representing a 150% increase over this period. The consumption of natural gas, however, increased by only 24% during this period. This disparity resulted from the growing application of hydraulic fracturing techniques around the U.S. to extract unconventional natural gas resources, which doubled the technology-weighted water intensity of California's natural gas consumption between 1990 and 2012, from 0.1 to 0.2 liters per cubic meters. Despite this growth, natural gas remained a relatively small component of the state's total EWF. However, regional variation in the water intensity and impacts in shale gas exploitation exist,[9] making natural gas an important energy product to monitor and manage in California's future energy-water portfolio.

The EWF of oil products consumed in California declined from 0.7 km^3 in 1990 to less than 0.5 km^3 in 2012, representing a 30% decrease. During this period, however, the quantity of oil products consumed in California declined by only 2%. Thus, the drop in oil's EWF was due primarily to shifting from more water-intensive oil production in California to less water-intensive production locations. In 1990, California produced around half of its domestic demand; however, by 2010 that number had dropped to 37%.[56]

The EWF of California's electricity consumption also decreased, from 1.2 km^3 in 1990 to 0.9 km^3 in 2012, though it reached a peak of 1.5 km^3 in 1995. The relatively high degree of variability compared to other energy products is due to the complexity of California's portfolio of generation sources and the wide range in water requirements for those different generation technologies. While total electricity consumption increased over this time period, most of this electricity was produced by relatively less water-intensive generation technologies, such as gas turbine or combined-cycle natural gas power plants, wind turbines, and solar photovoltaics. Hydroelectric generation, an extremely water-intensive form of electricity generation due to high evaporative losses from reservoirs, also decreased as a share of California's total electricity portfolio.

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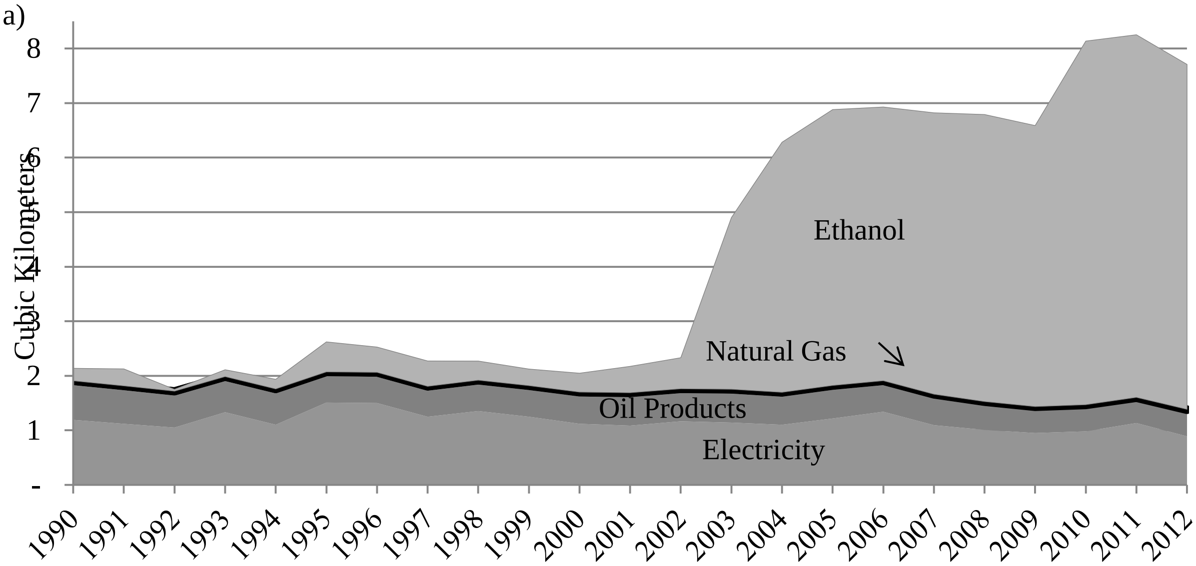
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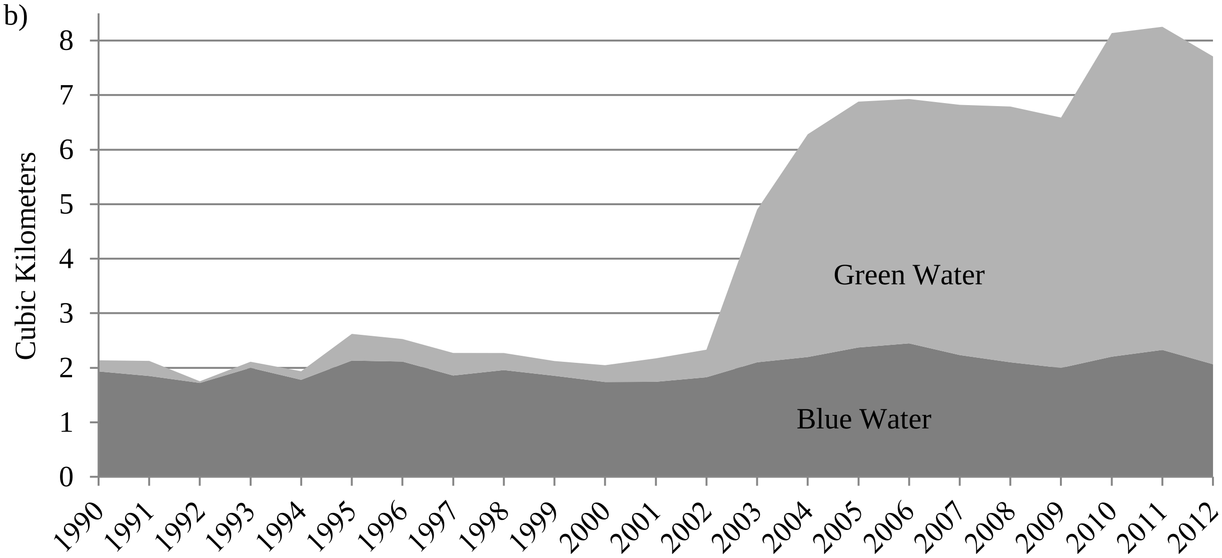
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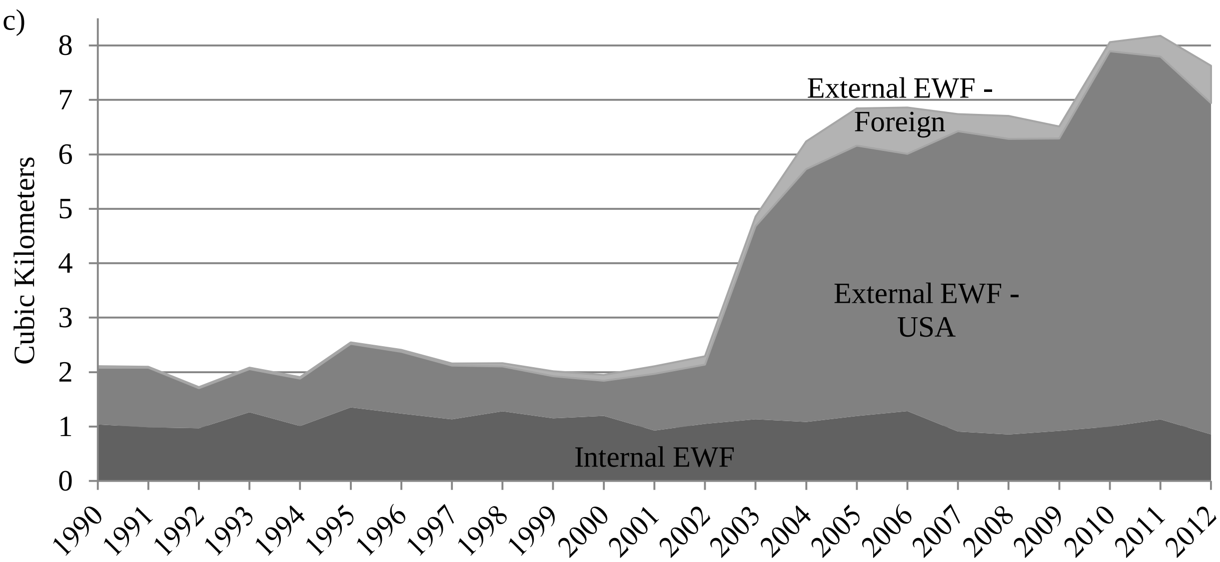
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Figure 3: California's energy-water footprint between 1990 and 2012, broken down by energy type (a), by green and blue water (b), and by internal and external locations (c).

Between 1990 and 2012, there have been dramatic changes in the "type" of water consumed, i.e., green vs. blue water (Figure 3b). In 1990, only 10% of California's EWF was green water and the remaining 90% was blue water, of which 63% was attributed to the electricity sector and 35% to oil products. Since 2003, however, green water has dominated California's EWF, and in 2012, blue water made up only 27% of the state's EWF. Plant-based ethanol accounts for all of this green water and 33% of the blue water, while electricity, oil products, and natural gas make up the remainder of the blue EWF.

The location of blue and green water use is relevant to local water resource concerns, as discussed earlier. Figure 3c shows California's EWF by internal and external sources, including in the U.S. and in foreign countries. In 1990, 1.0 km^3, or about half, of California's total EWF was internal to the state, i.e. using California's water resources (for comparison, this represented about 3% of total in-state consumptive use for all purposes).[57] By 2012, the volume of California's internal EWF was slightly smaller (0.9 km^3), but it made up just 11% of the state's total EWF. This means that all of the increase in California's EWF occurred outside of the state's borders. Indeed, much of this growth occurred in ethanol-growing regions of the US Midwest, but also substantially in other countries where ethanol and oil extraction have increased.

Discussion

An examination of the water footprint of California's energy system sheds light on how much, what type, and where water is consumed to produce the state's energy products. Understanding these linkages is of growing importance as the impacts of climate change on water and energy resources intensifies and as efforts to adapt to and mitigate these impacts are implemented. Our assessment highlights the need for more careful, integrated consideration of the implications of the water-energy nexus for water resource and energy system planning.

Our study shows that California's EWF has substantially increased over recent decades without utilizing more of the state's water resources, but rather relying more heavily on external sources of water. The increase in the EWF has been primarily associated with green water, i.e., precipitation that is used directly by biofuel crops in the field. While green water utilization may have added benefits in that it does not require pumping or associated infrastructure, it also links California's energy future directly to future precipitation and soil management regimes in biofuel-growing regions. To the extent that California's increased ethanol demand has relied on blue water, its energy system has also become linked to surface and groundwater management issues in those regions, such as the over-pumping of the Ogallala aquifer.[58] The Midwest drought of 2011-2012 highlights one risk of these linkages, as this drought constrained the ethanol supply and resulted in higher ethanol prices in California markets.[59,60] Moreover, foreign sources of ethanol, which have constituted up to 12% of California's supply, may face similar climate-related challenges.[61,62]

Although we did not present the grey water footprint of ethanol, factors provided from Mekonnen & Hoekstra (2010)[55] indicate that California's grey EWF associated with ethanol consumption ranged from one to two cubic kilometers per year (see Supporting Information). This grey water is associated with heavy use of fertilizers and pesticides, which then pollute local and regional waterways. As most of California's grey EWF related to biomass production within the Mississippi River Basin, California's energy system requires an additional 0.2% to 0.4% of the average annual discharge of the Mississippi River to bring pollutants to acceptable levels. We note that the initial use of ethanol as a substitute for methyl tert-butyl ether (MTBE) was brought about by water quality concerns in the state's urban groundwater basins, however this effort may have shifted water quality burdens outside the state rather than mitigate them altogether. This initial finding could be refined with further analysis of the pollutant persistence and relative impacts of these burdens. Nevertheless, these burdens may yet pose supply risks to California's energy system, as producing regions grapple with tradeoffs between high agricultural yields and low water quality from runoff.[63] Water quality concerns exist with other bioenergy sources as well as with the extraction and processing of other fuels and electricity generation.

Many of these observed trends in California's EWF can be linked to effects of the state's energy policies. The increased reliance on bioethanol was initially driven by the need for an alternative gasoline oxygenate following an executive order banning of MTBE in 2003.[64] More recent energy policies have encouraged additional ethanol blending in gasoline to meet state greenhouse gas targets. California's Low Carbon Fuel Standard (LCFS) of 2007, pursuant to its landmark Global Warming Solutions Act of 2006, has reinforced demand for bioethanol as a means to reduce the greenhouse gas intensity of transportation fuels. Although early LCFS policy assessments raised the issue of water demands and impacts from increased biofuel production,[65] any subsequent efforts to track or address those impacts through policy have been lacking.[66]

Expected trends in California's biofuel demand pose deeper consideration for integrated research and policy. Since 2009, bioethanol has been blended into California reformulated gasoline to 10% by volume, and an emerging market for E85 (85% ethanol fuel) is likely to increase the state's demand for bioethanol. These developments have been further abetted by a broader policy environment including the federal Renewable Fuel Standard (RFS), which since 2007 has mandated an increasing share of biofuels in U.S. transportation energy.[67] A recent study assessed the regional water impacts of various potential RFS-technology-policy scenarios, highlighting the need for attention to local effects and integrated approaches to federal policy.[68] Still, California holds a unique position in the national biofuels landscape, as the state with the largest demand yet little economically viable production capacity.[69] State-level energy policies have played, and will continue to play, a strong role in determining California's biofuel demand. Our research suggests that expected trends would substantially increase and further externalize the state's EWF in the future and that a closer examination of associated tradeoffs and climate risks is needed.

Shifts in other energy products have also driven the externalization of California's EWF. In-state crude oil extraction has declined since the mid-1980s, the demand having been made up by Alaskan oil initially, then imports from foreign sources. In this case, the blue water footprint of most sources of foreign oil is lower than that of California or Alaska, so California's blue EWF declined by 31% as a result of this shift (despite near constant overall supply). While this effect was unlikely intentional, it is not surprising that current efforts to "re-shore" energy production face increasing opposition on grounds of impacts to local water resources.[68] Still, if California's consumption of oil products does not wane, water impacts may continue to accrue inside and outside the state's borders.

Electricity is another sector where consideration of water resources inside and outside of California is important.[70,71] Imported electricity has long been an important source of the state's energy portfolio (30% of electricity on average), providing a flexible supply when hydropower potential is low or other factors restrict in-state generation. Yet, when California's grid operator outsources electricity, the state's EWF goes up. This is because out-of-state thermoelectric sources, especially older coal plans, tend to be more water intensive than newer in-state plants and coastal generators that use saline water for cooling.[72] Because this outsourced electricity also tends to be more greenhouse gas intensive, we see greenhouse gas-driven energy policies having a synergistic effect with reducing California's EWF. The opposite was found in China, where electricity production in the arid north uses dry cooling, and is therefore less water- intensive, however energy efficiency goes down in such systems, resulting in higher greenhouse gas-per-kilowatt hour produced.[73] Further synergistic effects can be found with energy conservation policies, which are not exclusively associated with climate change concerns.[74]

We conclude from our research that as California's energy policies have sought to mitigate climate change, water systems and resources, considered extremely vulnerable to the effects of climate change, have received little attention. When energy policies have considered impacts to water, such as the MTBE ban, policy outcomes may have simply shifted burdens rather than alleviate them. Given the exigencies of both climate change *and* the global water crisis, the interconnectedness of energy and water systems deserves closer attention in both academic and policy arenas. Climate and water goals are not mutually exclusive in energy policy; rather, to the extent that existing energy sources are fungible, climate and water goals can be achieved simultaneously. Additionally, many renewable sources of energy already have few water impacts.[53] Policy makers should seek to ask questions about unforeseen or unintended consequences of proposed energy policies and pathways. Analytical tools, such as the water footprint used here, provide a starting place and a framework to answer such questions; however, much more is needed.

Further research should focus more precisely on characterizing the relative impacts and risks of water footprint assessments such as California's EWF.[75] Weighting green, blue, and grey water footprint values by their relevant water stress, opportunity costs, and water quality impacts can inform better decision making by energy supply chain managers and energy policy designers. Interconnected water and energy systems need not be a source of risk for California or other entities; rather, integrated analysis and deeper understanding of these essentially linked resources can increase productivity at the energy-water nexus and simultaneously support climate change mitigation and adaptation strategies.

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Supporting Information Available

Supporting information includes statistics on California's energy product flows for each year from 1990 to 2012, calculation steps and data sources for Table 1, as well as grey water footprint estimates for ethanol consumption in California. This information is available free of charge via the Internet at http://pubs.acs.org/articlesonrequest/AOR-MFwK7SAD3ZFaD4vijhni.

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