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Abstract

Electricity and water systems are inextricably linked through water demands for energy generation, and through energy demands for using, moving, and treating water and wastewater. Climate change may stress these interdependencies, together referred to as the energy-water nexus, by reducing water availability for hydropower generation and by increasing irrigation and electricity demand for groundwater pumping, among other feedbacks. Further, many climate adaptation measures to augment water supplies—such as water recycling and desalination—are energy-intensive. However, water and electricity system climate vulnerabilities and adaptations are often studied in isolation, without considering how multiple interactive risks may compound. This paper reviews the fragmented literature and develops a generalized framework for understanding these implications of climate change on the energy-water nexus. We apply this framework in a case study to quantify end-century direct climate impacts on California's water and electricity resources and estimate the magnitude of the indirect cross-sectoral feedback of electricity demand from various water adaptation strategies. Our results show that increased space cooling demand and decreased hydropower generation are the most significant direct climate change impacts on California's electricity sector by end-century. In California's water sector, climate change impacts directly on surface water availability exceed demand changes, but have considerable uncertainty, both in direction and magnitude. Additionally, we find that the energy demands of water sector climate adaptations could significantly affect California's future electricity system needs. If the worst-case water shortage occurs under climate change, water-conserving adaptation measures can provide large energy savings co-benefits, but other energy-intensive water adaptations may double the direct impacts of climate change on the state's electricity resource requirement. These results highlight the value of coordinated adaptation planning between the energy and water sectors to achieve mutually beneficial solutions for climate resilience.

1. Introduction

Water and energy[5] systems worldwide are, by design and necessity, interdependent: water is an input for hydropower generation and thermal power plant cooling, and electricity powers the conveyance, treatment, usage, and disposal of water. These connections have commonly been referred to as the 'energy-water nexus' [1–5]. Climate change and the resulting shifts in the global hydrologic cycle [6, 7] may strengthen or strain these nexus connections in new and uncertain ways [8]. For example, temperature and precipitation changes could simultaneously

[5] The terms 'energy' and 'electricity' are used interchangeably in this analysis; for simplicity, only electricity is considered an energy source for the water cycle even though there may be other fuels used (such as diesel or natural gas) by certain water sector processes.

increase irrigation water demand and energy requirements for groundwater pumping, while reducing surface water and hydropower availability [9, 10]. Further, water sector adaptation measures commonly sought during long-term declines in surface water, such as water recycling, desalination, or groundwater recharge and withdrawal, are energy-intensive [4, 11–14]. Ignoring such interactive climate impacts in planning reduces the reliability of both systems and increases the risk of cascading failures [15–19].

Climate change impacts on the energy and water sectors have been studied extensively, yet several gaps remain in the literature. On the one hand, many climate vulnerability studies evaluate risks to individual sectors but have not holistically assessed compounding climate risks, such as those inherent in the dynamic relationship between closely coupled electricity and water systems [15, 19–21]. Typically these analyses evaluate electricity [9, 22, 23] or water systems [24] in isolation assuming the other remains fixed, or assess climate-related changes to supplies or demands separately [9, 25–27], making it difficult to account for interdependent impacts within and across sectors. On the other hand, many energy-water 'nexus' studies—focused on demonstrating how integrated systems' management improves efficiency, increases equitable resource access, and maximizes synergies [2]—characterize historical conditions without climate change [28–30]. The cross-sectoral tradeoffs of climate adaptation strategies, such as the energy footprint of alternative water supplies, are particularly understudied despite recognition that ignoring such externalities could lead to maladaptation, whereby one sector's adaptation strategies increase climate vulnerabilities in another [29, 31, 32].

Given such complexity, a conceptual framework describing key system linkages and dynamics is essential to guide analysis [33]. In the first half of this paper, we integrate findings from the fragmented literature into a generalized framework that catalogues how the relationship between electricity and water systems around the world may evolve under, and adapt to, climate change. This framework identifies the most critical cross-system climate impacts, adaptations, and feedbacks, to guide long-term planners on what to evaluate to comprehensively understand the scale and uncertainties of climate risks and adaptations of their resources. Because of regional variations in climate and infrastructure, in the second half of this paper we use a case study approach to apply the framework, focusing on the state of California.

As a semi-arid, populous, and agriculturally-intensive state, California's electricity and water systems are inextricably linked. On average 9% of California's electricity consumption is from water conveyance, treatment of drinking and wastewater, and agricultural pumping [30], and about 10% of electricity consumption is from water end-uses [34]. The water sector is especially energy-intensive because of inter-basin transfers between the wet Northern and dry Southern regions [35]. Additionally, about 15% of in-state electricity generation comes from hydropower [36,37]. California, considered one of the most 'climate-challenged regions in North America,' [38] is projected to face temperature increases, more frequent droughts, and significant loss of snowpack (a major source of water storage) [39–41]. Recent droughts foreshadow how the state's energy-water nexus may fare under these impacts of climate change [19]. California's water sector's drought responses transferred and compounded vulnerability to its electricity sector—increased groundwater pumping spiked electricity consumption, while hydropower deficits were replaced by greenhouse gas (GHG)-emitting fossil generation [37, 42]. In addition, the state has already seen several unprecedented climate-related impacts to the electricity grid, such as the August 2020 West-wide heat wave that triggered California's rolling blackouts [43].

In our case study, we quantify climate impacts by first synthesizing the range of individual water and electricity supply and demand changes projected by California-specific studies. Aggregating these projections, we estimate the overall change to the state's water and electricity annual resource balances due directly to climate impacts and indirectly to various potential climate adaptations by the end-century. We find that in the electricity sector, increased electricity demand for air-conditioning is the primary contributor to demand-supply imbalances. In the water sector, California's future water balance could span a wide range of shortage or surplus under climate change, driven mainly by large supply uncertainties. In the event of the worst-case water shortage, our results show that water-conserving adaptation measures provide large energy savings co-benefits, while other energy-intensive water adaptations may double the electricity resource imbalance caused by direct climate impacts alone. Through this analysis, we both quantify the compounding climate risks and demonstrate mutually beneficial adaptation opportunities that could arise with increased energy-water cross-sectoral coordination. We summarize the framework in section 2, the California case study methodology in section 3, and the case study results in sections 4 and 5.

2. Electricity-water nexus climate change adaptation framework

One of the core objectives of water and energy resource planners is to ensure adequate supplies to balance forecasted demands (subject to environmental, economic, and other constraints) [44–46]. Our framework (figure 1) thus distills findings from across the literature on how climate change may affect these key metrics of annual supply and

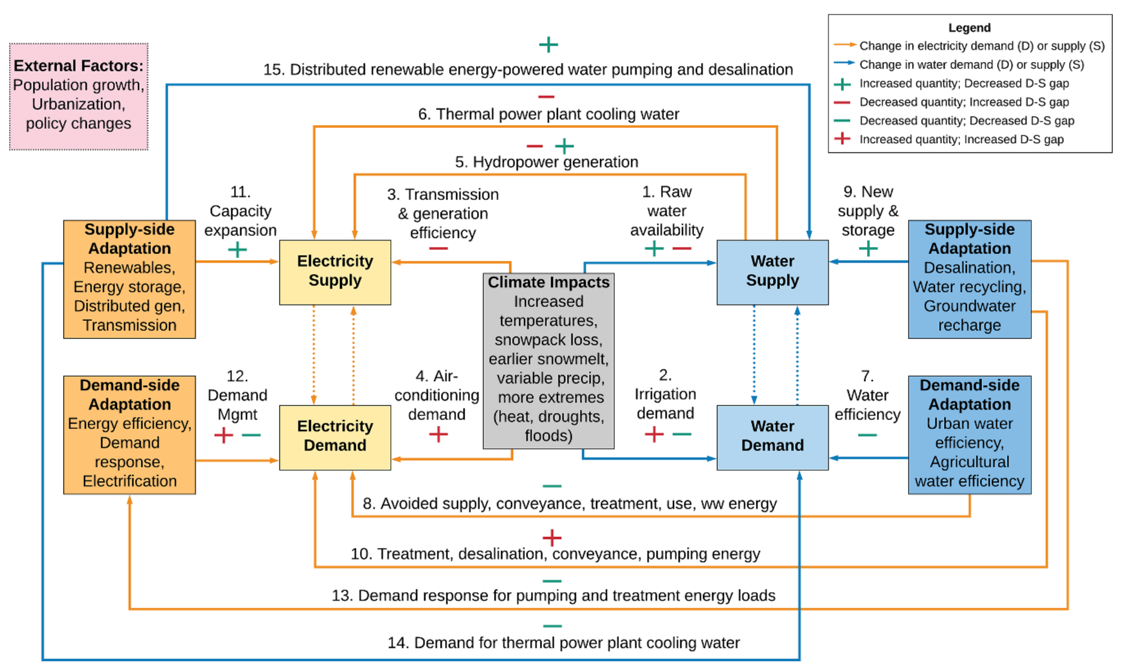

Figure 1. Electricity-water nexus climate change adaptation framework. Changes in electricity supply and demand quantities are denoted with solid orange links. Water quantity changes are denoted with solid blue links. Dotted lines indicate supply and demand must balance. Impacts that increase (decrease) quantities have + (−) and are green (red) if they decrease (increase) a system's demand-supply imbalance, i.e. difference or gap between demand and supply. Links with both + and − indicate disagreement in literature or multiple strategies with different effects (e.g. electrification increases while energy efficiency decreases demand; both are electricity demand-side adaptations).

demand quantities, and subsequent resource balances, of regional energy and water systems (linkages L_1 through L_{15}). This framework provides a first-order, system-level assessment tool to help resource planners and researchers identify the largest potential climate stressors, the range and order of magnitude of climate adaptation measures that may be needed, the possible compounding vulnerabilities due to cross-sectoral feedback effects, and the key uncertainties and knowledge gaps for further analysis.

The framework centers (grey box) on the most relevant[6] projected climate change impacts—increased temperatures, reduced snowpack, earlier snowmelt, changed precipitation patterns, and more frequent extremes. Across future GHG emission scenarios, global circulation models (GCMs) project climate change will increase surface temperatures worldwide [6]. Although there is uncertainty about future precipitation [26, 47], wetter regions, such as the northern high latitudes, are expected to become wetter, while some drier regions, such as in the mid-latitudes, may become drier [47–49]. Higher temperatures will also shift precipitation towards rain, while reducing accumulation and speeding melt of snowpack, a natural slow-release reservoir that meets warm-season water demands [27, 50–54]. In many regions, the frequency and intensity of storms and droughts will also increase [6, 55, 56]. These climate impacts directly affect water supply (raw water availability, L_1) and demand (irrigation water, L_2), and electricity supply (transmission and generation efficiency, L_3) and demand (air-conditioning, L_4). There are subsequent feedbacks, e.g. water supply shifts (L_1) affect electricity supply (hydropower generation, L_5 and thermoelectric cooling, L_6). In response to a resource imbalance, adaptation measures can reduce water demands (L_7) or augment water supplies (L_9), but may inadvertently affect electricity demand (L_8, L_{10}) and adaptations (L_{13}). Electricity adaptation strategies can expand supply-side capacity (L_{11}) and either reduce consumption through energy efficiency or increase consumption through electrification on the demand-side (L_{12}). Decarbonization of centralized electricity supply can reduce thermal power plant cooling water demands (L_{14}), and decentralized solar generation can power irrigation pumps and small-scale desalination to expand access to water supplies (L_{15}). Population growth, urbanization, and policy changes also affect energy and water systems.

In the framework diagram, changes in electricity supply and demand quantities due to climate impacts are denoted with solid orange linkages and water quantity changes are denoted with solid blue linkages. Dotted lines indicate supply and demand must balance in each system. Linkages that increase (decrease) quantities have + (−) and are green (red) if they decrease (increase) a system's demand-supply

[6] Because our focus is on long-term supply and demand balances, we omit climate impacts such as wildfires that primarily affect physical infrastructure and short-run reliability.

imbalance, i.e. difference or gap between demand and supply. Linkages with both + and − indicate disagreement in literature or multiple strategies with different effects (e.g. electrification increases while energy efficiency decreases demand; both are electricity demand-side adaptations). These linkages are reviewed below, with more details in the Supplemental Information (SI) (available online at https://stacks.iop.org/ERL/15/124065/mmedia).

2.1. Linkages L_1—L_6: climate impacts on water and electricity supply and demand

Studies typically use GCM data and a hydrological model to simulate unimpaired runoff, which feeds into a water resource management model to estimate impacts of changes in raw water availability, the water supply of a managed system ($\boldsymbol{L_1}$) [24, 57]. Such analyses find climate change will reduce or increase raw water availability primarily following the effect of regionally heterogenous precipitation patterns on runoff [26, 47–49], but results diverge due to GCM and hydrological model uncertainty [26, 47, 49]. For half the world's population dependent on snowpack for cold-season water storage [50], raw water availability may decline if snowmelt timing shifts and reservoirs cannot store earlier inflows that coincide with the flood season, when empty reservoir space must be maintained [27, 39, 51–53, 58–60].

Water demand for irrigated agriculture comprises 85% of global water consumption [27]. In many regions, climate change is projected to raise temperatures, decrease precipitation, and increase evapotranspiration (ET) [59], together affecting soil moisture and increasing irrigation water demand ($\boldsymbol{L_2}$) [25, 49, 61–63]. However, factors such as ET differ across hydrological models, GCMs, and observational data [47, 64]. For example, some studies account for increased atmospheric CO_2 causing plant stomata to reduce transpiration, thereby decreasing irrigation water demand [64–67]. Others contend that increased CO_2 fertilizes photosynthesis [63, 65], which could have an offsetting effect of speeding crop growth, enabling multiple plantings, and increasing annual irrigation requirements.

In the electricity sector, climate change could directly reduce supplies through increased transmission line losses and decreased generator efficiencies ($\boldsymbol{L_3}$). Resistive transmission losses increase as higher ambient temperatures lower radiative cooling of lines [9, 23, 68–70], requiring additional electricity generation to compensate [69, 71]. Higher ambient temperatures also lower both thermoelectric [23, 72, 73] and solar generating efficiencies [72, 74]; wind generation impacts are uncertain [9, 22, 23, 72].

Higher temperatures will raise electricity demand ($\boldsymbol{L_4}$) through more frequent usage (intensive effect) and new adoption (extensive effect) of air-conditioning [75–78]. In some regions, increases in demand may be partially offset by reduced heating, but demand is still projected to rise annually [9, 75, 78] and most significantly during summer peak times [71, 79, 80]. Electricity demand growth is especially pronounced in regions with both rising temperatures and incomes [76, 81].

Lastly, climate change affects electricity supply—hydropower ($\boldsymbol{L_5}$) and thermoelectric generation ($\boldsymbol{L_6}$)—through feedbacks of water supply changes ($\boldsymbol{L_1}$). Hydropower generation will change primarily according to raw water availability [9, 22, 23, 82, 83], and based on snowmelt dependence [9, 22, 50]. Hydropower reservoirs relying on snowpack storage [84, 85] and those with flood control objectives may have reduced summer and annual generation due to earlier snowmelt [9, 86], although larger reservoirs have greater operational flexibility and less sensitivity to these impacts [57, 85]. Meanwhile, with potentially reduced raw water availability and higher water temperatures, generation from thermoelectric plants relying on cooling water may decline [9, 22, 87–89]. The impact depends largely on the climate sensitivity of the cooling technology (once-through and recirculating) and water source (surface, groundwater, seawater, wastewater) [4, 83]. Dry-cooling systems use no water and are not sensitive to these water-related climate impacts, but because they are less effective at heat rejection compared to wet-cooling systems, switching to dry-cooling could reduce a thermoelectric generator's overall efficiency performance by 2%–7% [4, 90].

2.2. Linkages L_7—L_{15}: climate adaptations for water and electricity and their feedbacks

Traditional water supply management approaches, such as construction of reservoir storage or conveyance infrastructure, may be limited in the future by over-allocated rivers, social and ecological impacts, and costs [25, 91–94]. A combination of strategies reducing water demand ($\boldsymbol{L_7}$) and augmenting supplies with non-traditional sources ($\boldsymbol{L_9}$) may therefore be needed to adapt to climate-driven water imbalances [25, 95]. Urban demand-side adaptations include indoor savings from high-efficiency appliances, conservation, and leak repair [92, 96, 97]; and outdoor savings from drought-tolerant plants, reduced planted area, and optimized irrigation [96]. Agricultural demand-side adaptations include integrated crop water management (reducing evaporative soil moisture loss) [98, 99], irrigation efficiency [100] (although potentially reducing return flows basin-wide [101]), crop-switching, [102–104] and land fallowing [91]. Groundwater banking, water recycling, and desalination are common supply-side adaptations[105]. Groundwater banking or recharge programs artificially infiltrate surface water (including flood or stormwater [91, 105]) into aquifers for withdrawal in dry years [106]. Treated wastewater can be reused for irrigation, or recycled further for potable use [92, 93, 97, 105]. Desalination treats seawater (35 000–45 000 ppm salinity) or brackish water (1500–15 000 ppm salinity) to drinking water quality (<500 ppm salinity) [4, 107].

These water sector adaptations have varying energy intensities (energy consumption per unit volume of water). Both urban and agricultural demand-side strategies save energy upstream by avoiding water supply and conveyance (L_8) [13]. Urban conservation further avoids energy from drinking water and wastewater treatment[97] and from water heating [92]. Conversely, supply-side water adaptations from unconventional sources tend to increase energy demand (L_{10}) [108]. Groundwater banking programs require pumping to withdraw water from storage [11]. Water recycling uses advanced treatment to reach potable quality and pumps treated water into the distribution system (direct potable reuse) or into groundwater or reservoir storage (indirect potable reuse) [13, 93, 109]. Desalination, most commonly from reverse osmosis, is the most energy-intensive adaptation; by some estimates seawater desalination uses 25x more energy than groundwater pumping[4] and 2x more than recycling [97]. However, the impact of this energy consumption on the grid can be managed through electric utility programs that shift the timing of demand to coincide with renewable energy generation (L_{13}) [4, 110].

Electricity sector adaptations, often primarily motivated by climate change mitigation, include supply expansion and decarbonization (through utility-scale renewable generation, storage, and transmission capacity, as well as distributed generation, L_{11}), and demand management (energy efficiency, electrification of end-uses such as transportation, and demand response, L_{12}). Supply-side strategies that transition from thermal to non-water-intensive solar and wind generation [111–113] decrease water demand for cooling (L_{14}) [90, 114]. Distributed, off-grid generation from solar PV can also power irrigation pumps to expand access to surface or groundwater supplies and drip or sprinkler irrigation (L_{15})[115–117]. Small-scale, distributed solar-powered desalination has also been deployed to augment water supplies in several regions [4].

2.3. External factors: population growth, urbanization, policy changes

Population growth, urbanization, and policy changes also compound or offset climate impacts on energy and water systems [19, 25, 108]. Population growth increases resource demand [26, 118], but impacts vary by density (urbanization). For example, if urban population growth creates sprawl and encroaches on agricultural lands, demand for more energy-intensive urban water displaces irrigation water demand [119]. Policy changes, such as regulations limiting groundwater extraction, also affect a system's water supply portfolio and energy intensity [108, 120]. For electricity systems, decarbonization policies may increase reliance on climate-sensitive hydropower resources [82, 83].

3. Methods and data: California case study

We apply our framework to California by: (1) synthesizing the range of climate impacts on linkages L_1 through L_5 from existing studies (2) estimating the subsequent aggregate effect of climate change directly on both systems' annual resource balances, and (3) calculating energy consumption (L_8, L_{10}) tradeoffs of different water adaptation strategies (L_7, L_9) in the event of a worst-case water shortage.

We exclude changes to cooling water (L_6 or L_{14}) because California already uses minimal freshwater,[7] and must further reduce thermal generation (excepting small shares of biomass and solar thermal) to meet its 2045, 100% carbon-free energy goal [121, 122]. We also omit solar PV and wind generation losses in L_3 because of uncertain end-century resources and nominal expected impacts (solar capacity declines <2%) [72]. Subsequent analysis is planned for L_{11} through L_{13}, L_{15}, and external factors[8].

3.1. Synthesis of climate impacts on water and electricity resource balances

We review literature quantifying climate change impacts on California's energy and water supplies and demands, excluding analyses with limited geographic coverage (apart from irrigation and hydropower which are typically analyzed regionally), and collect results from 18 studies for L_1 through L_5. For each linkage, we cull the maximum and minimum of annual percentage changes to resources projected for end-century (2070–2100)[9], characterizing the combined uncertainty from different methodologies, GCMs, and emissions scenarios across studies (more details on studies in table S2).

[7] In 2018, thermal power plants in California withdrew and consumed approximately 0.02 Billion m^3 of freshwater, comprising 0.02% of average annual water supplies[151].

[8] Our analysis focuses on end-century climate impacts, however, in the nearer term, California's policies to electrify transportation, from internal combustion to electric vehicles (EVs), and buildings, from natural gas to electric space and water heating, may have a greater impact on increasing electricity demand than climate change (L_{12}). For example, one analysis for 2050 projects high levels of building electrification may increase electricity demand as much as 3x times as climate increases the demand for air-conditioning [152]. However, given that end-century climate change impacts on air-conditioning could be 2x higher than in mid-century [75, 145], and the uncertainty of the future building stock and vehicle fleet by the end-century study period, we have not included these effects in our end-century analysis.

[9] The end-century is the time period for which we found the most studies across all the linkages. SI table S2 includes additional projections for mid-century where available, such as from [153–155].

Table 1. Calculations for climate change impacts on California annual water and electricity resource balances. L_1 and L_2 are calculated with 2002–2015 average urban and agricultural water balance data from the California Department of Water Resources [123] in Billion cubic meters, Bm^3. Electricity linkages are calculated with residential and commercial building (L_4) and total (L_3) 2001–2018 average electricity consumption data from the California Energy Commission [124], and hydropower generation data (L_5) averaged 2002–2018 from the Energy Information Administration [125] in terawatt-hours, TWh. Irrigation demand changes (L_2) are calculated for the main agricultural regions (Sacramento Valley (Sac), San Joaquin Valley (SJV), Tulare Lake (Tul)) and hydropower changes are calculated for high- (>300 m) and low-elevation generators (L_5).

Annual water supply changes	Annual water demand changes
$\boldsymbol{L_1}$, **Raw water availability** $\Delta\left[Bm^3\right] = \left(Total\,urban\,and\,ag.\,water,\,53\,Bm^3\right) * (\%\Delta)$	$\boldsymbol{L_2}$, **Irrigation water demand** $\Delta\left[Bm^3\right] = \left(Irrigation\,demand_{Sac},\,10\,Bm^3\right) * \left(\%\Delta_{Sac}\right) + \left(Irrigation\,demand_{SJV},\,9\,Bm^3\right) * \left(\%\Delta_{SJV}\right) + \left(Irrigation\,demand_{Tul.},\,14\,Bm^3\right) * \left(\%\Delta_{Tul.}\right)$
Total change in annual water balance	
Annual water balance $\Delta\left[Bm^3\right] = L_1 - L_2$: **Worst-case water balance** $\Delta\left[Bm^3\right] = min(L_1) - max(L_2)$ **Best-case water balance** $\Delta\left[Bm^3\right] = max(L_1) - min(L_2)$	
Annual electricity supply changes	Annual electricity demand changes
$\boldsymbol{L_3}$, **Supply impact of transmission losses** $\Delta[TWh] = (Total\,elec.\,consumption,\,278\,TWh) * (\%\Delta)$ $\boldsymbol{L_5}$, **Hydropower generation** $\Delta[TWh] = (Hydro\,generation_{low-elev.},\,11\,TWh) * (\%\Delta_{low-elev.}) + (Hydro\,generation_{high-elev.},\,20\,TWh) * (\%\Delta_{high-elev.})$	$\boldsymbol{L_4}$, **Air-conditioning demand** $\Delta[TWh] = (Res.\,and\,com.\,elec.\,consumption,\,190\,TWh) * (\%\Delta)$
Total change in annual electricity balance	
Annual electricity balance $\Delta[TWh] = (L_3 + L_5) - L_4$: **Worst-case electricity balance** $\Delta[TWh] = (min(L_3) + min(L_5)) - max(L_4)$ **Best-case electricity balance** $\Delta[TWh] = (max(L_3) + max(L_5)) - min(L_4)$	

We standardize these ranges as absolute changes in water and energy volumes, applying the climate perturbation percentages to historical electricity and water stocks[10] (table 1 and S3). Finally, to calculate the overall bounding 'worst-case' and 'best-case' range of climate impacts on annual state water and energy balances, for each system the maximum of demand changes are subtracted from the minimum of supply changes, and the minimum of demand changes are subtracted from the maximum of supply changes, respectively. A resulting balance change that is negative indicates shortage (demand exceeds supply), and a positive balance change indicates surplus (supply exceeds demand). These sign conventions and method of calculation are appropriate to bound the systemwide worst-case and best-case because the climate impacts on demand and supply are coincident i.e. supply will decrease at the same time as demand will increase and vice versa.

[10] The literature we review projects average annual resource changes due to climate change. Therefore, we apply the percentage changes to average annual historical levels of water and electricity supplies and demands. However, there is significant inter-annual resource variability in the water sector (e.g. in a recent wet year, 2011, annual surface water supply in California was about twice that of a drought year, 2015) [123]. Analysis of the impact of this inter-annual variability on energy and water balances under climate change is an area for future research.

3.2. Climate adaptations for water shortages and their energy tradeoffs

If the worst-case, upper end of the water shortage calculated in section 3.1 is realized, significant application of adaptation measures that either augment water supplies or reduce water demands may be needed. We estimate the energy balance feedback ($\boldsymbol{L_8}$, $\boldsymbol{L_{10}}$) from residential water conservation, agricultural water conservation, groundwater banking, water recycling for indirect potable reuse, and desalination adaptation measures ($\boldsymbol{L_7}$, $\boldsymbol{L_9}$) that could fill the maximum water shortage volume.

As shown in table 2, we first calculate the net energy intensity $\left(NEI_{i,j}\right)$ of each adaptation measure, by summing the average energy intensities of all processes required to implement the measure (i.e. treatment, pumping, etc.) [126] as EI_i, and subtracting EI_j, the energy intensity of the water source it may replace because of climate impacts [105]. These energy intensity values are averages across studies as described in S3 [10, 11, 13, 30, 34, 108, 127–130,133–137].

$$NEI_{i,j} = EI_i - EI_j$$

where,

$EI_i =$ Energy intensity of adaptation i, summing energy intensities of all associated processes

Table 2. Net energy intensity of water adaptations in California. Net energy intensity of a water adaptation measure $NEI_{i,j}$ is the difference in energy intensity of the substituted water source EI_j and adaptation measure EI_i. EI_i is the sum of energy spent in implementing the measure, using statewide averages of associated processes listed in the table. Negative EI_i and $NEI_{i,j}$ values indicate energy savings, and positive values indicate energy consumption. EI_i of residential water conservation includes energy savings from avoided water treatment, urban distribution, water heating, and wastewater treatment. EI_i of agricultural water conservation includes energy savings from avoided agricultural distribution and irrigation. EI_i of groundwater banking includes energy for groundwater pumping. EI_i of water recycling includes energy for incremental treatment above wastewater treatment for indirect potable reuse, and for distribution from the treatment plant to storage. EI_i of desalination includes energy for reverse osmosis treatment, averaged across values for seawater and brackish water, and for distribution from the treatment plant. Three EI_j are included: local surface water (0.09 kWh m^{-3}), California supply-weighted average (0.32 kWh m^{-3}), and the average across delivery points of the State Water Project conveyance system (1.55 kWh m^{-3}). EI_i references: [10, 11, 13, 30, 34, 108, 127–130,133–137].

Water adaptation measures i	Calculation of EI_i of adaptation measure [kWh m^{-3}]	EI_i of adaptation measure [kWh m^{-3}]	$NEI_{i,j}$ swith EI_j of local surface water [kWh m^{-3}]	$NEI_{i,j}$ with EI_j of CA avg. water source [kWh m^{-3}]	$NEI_{i,j}$ with EI_j of State Water Project water [kWh m^{-3}]
L_7, Residential water conservation	$-(treatment\,energy, 0.17,$ $+urban\,distribution\,energy, 0.27$ $+res.\,water\,heating\,energy, 3.16$ $+wastewater\,treat.\,energy, 0.69)$	−4.29	−4.39	−4.62	−5.84
L_7, Agricultural water conservation	$-(ag.\,distribution\,energy, 0.21$ $+irrigation\,energy, 0.09)$	−0.30	−0.39	−0.62	−1.84
L_9, Groundwater banking	$groundwater\,pumping\,energy, 0.38$	0.38	0.28	0.05	−1.17
L_9, Water recycling for potable reuse	$incremental\,treat.\,energy, 0.95$ $+recycled\,dist.\,energy, 0.27$	1.22	1.13	0.90	−0.32
L_9, Desalination	$desal\,treatment\,energy, 2.55$ $+desal\,dist.\,energy, 0.29$	2.84	2.75	2.52	1.30

Table 3. Scenarios of water sector climate adaptations. In corner case scenarios, the water shortage volume WSV_i is equal to 100% of the worst-case water shortage volume (18 Bm^3) calculated in section 3.1. In portfolio scenarios, WSV_i contributions of several measures sum to address the worst-case water shortage. Water conservation and water recycling are capped at their limits,1.8 Bm^3/year [96] and 6.7 Bm^3/year [12, 13], respectively.

Corner case scenarios	WSV_i filled by adaptation measures	Portfolio scenarios	WSV_i filled by adaptation measures
Corner case 1:		**Portfolio 1:**	
100% Residential water conservation	18 Bm^3	10% Residential water conservation	1.8 Bm^3
		18% Agricultural water conservation	3.2 Bm^3
		18% Groundwater banking	3.2 Bm^3
		37% Water recycling for potable reuse	6.7 Bm^3
		18% Desalination	3.2 Bm^3
Corner case 2:		**Portfolio 2:**	
100% Agricultural water conservation	18 Bm^3	10% Residential water conservation	1.8 Bm^3
		37% Water recycling for potable reuse	6.7 Bm^3
		53% Desalination	9.5 Bm^3
Corner case 3:		**Portfolio 3:**	
100% Groundwater banking	18 Bm^3	10% Residential water conservation	1.8 Bm^3
		90% Desalination	16.2 Bm^3
Corner case 4:		**Portfolio 4:**	
100% Water recycling for potable reuse	18 Bm^3	37% Water recycling for potable reuse	6.7 Bm^3
		63% Desalination	11.3 Bm^3
Corner case 5:			
100% Desalination	18 Bm^3		

in $kWh\,m^{-3}$, {Residential water conservation, agricultural water conservation, groundwater banking, water recycling, desalination}.

EI_j = Energy intensity of substituted water source j in $kWh\,m^{-3}$, $j \in$ {local surface water, California volume-weighted average water source, State Water Project deliveries}.

For example, if climate change effectively reduces deliveries via the energy-intensive State Water Project (SWP) inter-basin transfer, the $NEI_{i,j}$ of an adaptation measure is net of avoided SWP conveyance energy. Because of uncertainties in where and how much of each water source may be substituted, for each adaptation we test three EI_j sensitivities that each assume a single source of substituted water j—local surface water (0.09 kWh m^{-3}), a weighted average of all California water supplies (0.32 kWh m^{-3}), and SWP deliveries (1.55 kWh m^{-3}) (details in S3).

We then construct five corner case scenarios of each individual adaptation measure addressing 100% of the worst-case maximum water shortage volume, and four portfolio scenarios, ranging from most to least diversified, combining multiple measures capped at their feasible volume limits (table 3). Portfolio 1 caps residential (indoor plus outdoor) water conservation at 1.8 Bm^3/year [96] and water recycling at 6.7 Bm^3/year [12, 13] with the remaining shortage equally satisfied by groundwater banking, agricultural conservation, and desalination. Portfolios 2 through 4 cap residential conservation and recycling, and desalination meets the remaining volume.

Finally, for each combination of adaptation scenario s and substituted water source j, we calculate the overall energy balance impact, $EB_{s,j}$, as the sum-product of the $NEI_{i,j}$ of included adaptation measures from table 2 and associated water volumes WSV_i from table 3.

$$EB_{s,j} = \sum_{i=1}^{n} \left(NEI_{i,j}\right) \times \left(WSV_i\right)$$

where,

$NEI_{i,j}$ = Net energy intensity for adaptation measure i for substituted water source j in $kWh\,m^{-3}$

WSV_i = Water shortage volume filled by adaptation measure i in m^3, $i \in$ {Residential water conservation, agricultural water conservation, groundwater banking, water recycling, desalination} and $j \in$ {local surface water, California volume-weighted average water source, SWP deliveries}.

Table 4. Range of end-century annual climate change impacts on California electricity and water systems. Details on all studies referenced for each linkage are in SI **table 6.**

Linkage	End-century annual % Δ from literature (−decrease/+increase)	Ref.	Calculated end-century annual absolute Δ
Supply-side L_1, Raw water availability	−25% to +46%	[57, 132, 133]	−13 to +24 Billion m3
Demand-side L_2, Irrigation water demand	Sacramento Valley: −2% to +31% San Joaquin Valley: 0% to +7% Tulare Lake:+3% to +7%	[60, 61, 102, 135, 136]	+0.2 to +5 Billion m3
Worst-case to best-case change in water balance (−shortage/+surplus)			**−18 to +24 Billion m3**
Supply-side L_3, Transmission energy losses	−0.14% to 0%	[69, 137]	−0.4–0 TWh
L_5, Hydropower generation	Low elevation:−27% High elevation:−20% to +14%	[83–85, 138–140]	−7 to −0.2 TWh
Demand-side L_4, Air-conditioning demand	+3% to +18%	[74, 141]	+6 to +34 TWh
Worst-case to best-case change in electricity balance (−shortage/+surplus)			**−42 to −6 TWh**

4. Case study results and discussion

For California's water system, we find that by end-century, climate change may cause an annual average imbalance ranging from an 18 Bm^3 shortage in the worst-case to a 24 Bm^3 surplus in the best-case (table 4, figure 2(a)). This large range is dominated by widely differing estimates (25% decrease to 46% increase) of raw water availability (L_1) [57, 131, 132]. Despite rich literature on California hydroclimatic phenomena and on subsets of its water system [12, 24, 39, 138] we find relatively little research estimating changes in California's total managed water supply. Further, studies differ on the degree to which any increased November through March runoff under climate change could be captured for water supplies, due to concurrent reservoir flood control requirements [39, 57]. Increased irrigation water demand (L_2) contributes the remaining imbalance; demands could decrease 2% or increase up to 31% within California's individual agricultural regions [61, 62, 104, 139, 140]. The variation reflects assumptions for ET and plant physiology [139], and regional differences in the share of water-intensive crops [61, 62].

In California's electricity system, climate change may create an annual imbalance ranging from a shortage of 6 TWh in the best-case up to a shortage of 42 TWh in the worst-case (table 4, figure 2(b)). We find that higher electricity demand for air-conditioning (L_4) is the largest contributor (3% increase to 18% increase) [75, 145], concurring with prior work [71]. During summer months, peak demand may increase more sharply (4% to 20% increase) than total annual demand [70, 145, 146]. The ranges reflect differences across studies in GCMs, spatial resolution, and inclusion of both extensive and intensive growth [75]. On the supply-side, California's annual average hydropower generation (L_5) could decrease 27% or increase up to 14% by end-century, within individual high- and low-elevation regions [84–86, 142–144]. Absolute declines are greatest for high-elevation hydropower (which contributes two-thirds of total average hydropower generation) and hot/dry GCM projections, worsening with droughts[11]. Despite disparities in annual estimates, studies agree seasonally—average hydropower generation (and spill) is projected to increase over winter and spring, and decrease up to 55% over summer, which may exacerbate grid reliability planning challenges. Lastly, studies project a nominal 0.1% increase in transmission resistive losses (L_3) [70, 141].

If climate change leads to water imbalances, our analysis finds that a wide range of energy impacts is possible from adaptations that meet the 18 Bm^3 worst-case shortage. Figure 3 shows that the energy balance ($EB_{s,j}$) impacts of several adaptation scenarios (including corner cases and portfolios), are on the same order of magnitude or even surpass direct climate impacts on the energy system.

Among the adaptation corner case scenarios, consistent with prior studies [96, 126, 147–149], we find that strategies that rely strongly on conservation measures, particularly in urban areas, could substantially reduce energy requirements for water sector adaptation. Residential conservation saves the most energy (about 80–110 TWh saved) by avoiding energy-intensive end-uses, conveyance, and treatment. Conversely, if the water shortage is met entirely with desalinated water, the energy impact (20–50 TWh of additional demand) could exceed that of direct climate change induced shortages in the electricity sector, from hydropower generation, transmission losses, and air-conditioning combined.

[11] For example, hydropower generation in 2015, the worst year of the recent 2012–2016 drought, decreased to about 50% of the 2002–2018 average level [36, 125]. Droughts are projected to become more frequent in California under climate change [156].

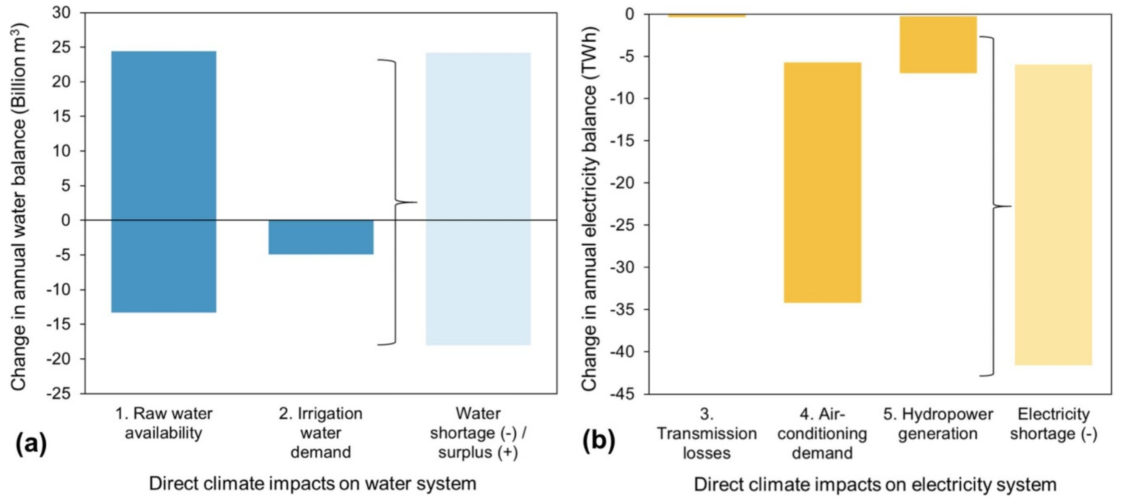

Figure 2. (a) End-century climate impacts on California annual water balance. (b) End-century climate impacts on California annual electricity balance. The upper and lower ends of the bars for each linkage show the maximum and minimum calculated absolute change as it affects the resource balance. The water and electricity shortage/surplus bars are respectively the sum of the supply and demand component changes and represent the aggregate worst-case and best-case changes in resource balances. Positive indicates surplus, negative indicates shortage.

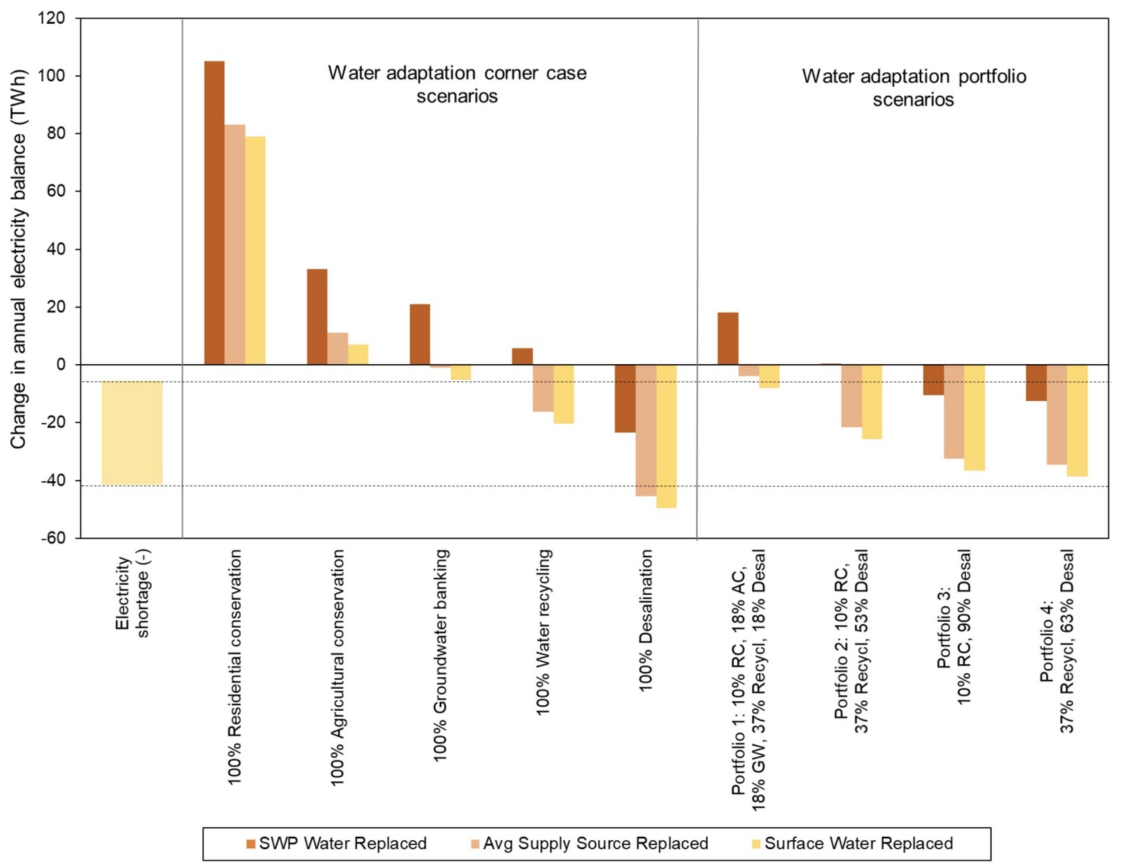

Figure 3. Energy impacts of water adaptations compared to direct climate impacts on California electricity balance. Dotted lines indicate the range of the annual electricity shortage from direct climate change impacts by the end-century in California (from figure 2(b)). The panels on the right show the annual energy consumption or savings impacts of water adaptations to meet the worst-case end-century water shortage in California. Corner cases meet the full water shortage with a single adaptation; portfolios include combinations of measures, as indicated by the percentage share. RC = Residential conservation; AC = Agricultural conservation; GW = Groundwater banking; Recylc = Water recycling for potable reuse; Desal = Desalination. Colors indicate water sources replaced by adaptations. SWP = State Water Project. Positive indicates surplus, negative indicates shortage.

Diversified portfolios of both demand-side and supply-side adaptations reduce overall energy impacts, while also overcoming some of the physical limits [4, 12, 13], infrastructure costs [92], public opinion [97, 105], and water pricing [97] implementation barriers that make relying on corner cases unrealistic. For example, with a mix of residential and agricultural conservation, groundwater recharge, water recycling, and desalination, we find that Portfolio 1's energy impact (ranging from 18 TWh saved to 8 TWh of additional demand) could completely or near completely offset direct climate impacts on the energy imbalance. Conversely, energy impacts increase with less diversified strategies relying primarily on supply-side measures [108]. Portfolios 2, 3, and 4 nearly double the energy imbalance, like the most energy-intensive corner cases, because of their high shares of desalination and water recycling.

We find that the source of water substituted by an adaptation is nearly as important to the overall energy impact as the energy demand to implement the adaptation itself. All adaptation corner cases except for desalination save energy when substituting energy-intensive SWP water (using the average energy intensity across delivery points), whereas if a local or an 'average' water source is replaced, groundwater banking, recycled water, and desalination would still create energy shortages. The most diverse Portfolio 1 saves energy if replacing SWP deliveries, while the replacement of average and local surface water supplies still adds to the energy shortage.

5. Summary and conclusions

Previous analyses have characterized either current electricity and water system connections, or future climate change vulnerabilities of individual system components in isolation. This study unites these two threads of literature and presents a generalized framework which can guide resource managers on evaluating climate impacts on the energy-water nexus for long-term planning. While this paper applies the framework to the California context, the overall concept can be broadly used by planners and researchers to conduct a first-order, aggregate assessment of cross-sectoral climate vulnerabilities and the tradeoffs among available adaptation technologies in regions with closely coupled electricity and water systems. The importance of particular linkages will differ by region based on hydroclimatic conditions and infrastructure. For example, generation losses depend on the share of thermoelectric plants that rely on cooling water, and water supply changes depend on region-specific snowpack storage, groundwater dependency, and reservoir operations. Further, the ability to realize co-benefits and minimize unintended energy impacts of water adaptations will also depend on a number of physical, institutional, environmental, and economic constraints[31] that are important criteria for future study and decision-making.

When applying this framework to California, we find that the range of potential climate-driven gaps between supply and demand are much larger for the water system (spanning both shortage and surplus) than the electricity system, reflecting large water supply uncertainties by end-century. To better support water and electricity planning efforts, subsequent research can explore in more detail how projected hydroclimatic variability and change interacts with the operations of constrained water infrastructure[22,24], especially in the nearer term, at more refined geographic and temporal scales, and during extreme events [68, 150]. For example, given available data, our estimates of annual average climate change impacts on energy and water resources in California potentially underestimate the severity of demand-supply imbalances during the summer months when several factors coincide (e.g. irrigation demand increases, raw water decreases, hydropower decreases, and air-conditioning increases).

Overall our findings imply that water sector adaptations could significantly compound the direct effect of climate change on the electricity system, suggesting the need for grid planning to incorporate not only direct impacts (such as future air-conditioning growth and hydropower reductions), but to also coordinate with water resource planners to prioritize energy considerations in decision-making and to anticipate water sector adaptations in electricity demand forecasts. Closer cross-sectoral adaptation planning could enable jointly funded R&D, customer incentives, and programs for water conservation, which would have the greatest mutual water and energy saving benefits and help ensure reliable services in both sectors. Climate change will bring new and uncertain challenges to strongly interdependent electricity and water systems. This analysis demonstrates the substantial benefits of coordinated climate adaptation planning between the electricity and water sectors to increase system resilience worldwide.

Data availability statement

The data that support the findings of this study are available upon reasonable request from the authors.

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