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The Energy Trade-Offs of Transitioning to a Locally Sourced Water Supply Portfolio in the City of Los Angeles

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Abstract: Predicting the energy needs of future water systems is important for coordinating long-term energy and water management plans, as both systems are interrelated. We use the case study of the Los Angeles City's Department of Water and Power (LADWP), located in a densely populated, environmentally progressive, and water-poor region, to highlight the trade-offs and tensions that can occur in balancing priorities related to reliable water supply, energy demand for water and greenhouse gas emissions. The city is on its path to achieving higher fractions of local water supplies through the expansion of conservation, water recycling and stormwater capture to replace supply from imported water. We analyze scenarios to simulate a set of future local water supply adoption pathways under average and dry weather conditions, across business as usual and decarbonized grid scenarios. Our results demonstrate that an aggressive local water supply expansion could impact the geospatial distribution of electricity demand for water services, which could place a greater burden on LADWP's electricity system over the next two decades, although the total energy consumed for the utility's water supply might not be significantly changed. A decomposition analysis of the major factors driving electricity demand suggests that in most scenarios, a structural change in LADWP's portfolio of water supply sources affects the electricity demanded for water more than increases in population or water conservation.

Keywords: urban water system; local water supply; water-energy nexus; electricity demand; index decomposition analysis

1. Introduction

Transition to a low carbon and sustainable society will involve multi-sectoral and multi-disciplinary approaches to support decision-making. Reducing the emissions associated with energy consumption is an obvious component of any robust greenhouse gas mitigation plan, and the water sector is one of the largest energy loads in most municipal regions, making it a valuable opportunity for greenhouse gas reductions [1]. Energy is needed to source, convey, treat and distribute water to residential, commercial and industrial users. Energy is also consumed for wastewater collection and treatment, in order to ensure the safe discharge of treated wastewater effluent into the environment [2]. Based on a 2013 study, about 69 billion kWh or 2% of total electricity consumption in the U.S. was consumed for drinking water supply and wastewater management systems [3]. In some water-stressed regions where local freshwater is not abundant, water systems can consume much more energy than average through large pumping projects or advanced treatment of degraded water sources. California, for example, depends on large pumping networks to deliver raw water from where it originates to large water demand regions in Southern California. Consequently, in California, roughly 7.7% of total electricity was consumed in the water sector in year 2001 based on a study published in 2010 [4].

The energy requirements of water supplies are expected to increase in regions with expected population growth, stricter environmental regulations, increasing water scarcity, growing groundwater depletion, and higher dependence on long-distance inter-basin transfers [5], particularly in areas facing extreme and prolonged droughts [6,7]. Several water-stressed regions and cities have formed initiatives to address the rising challenges of reliable water supply and climate resiliency. In arid and semi-arid parts of the U.S. (such as California and Arizona) and across the world (such as in Israel, Australia, and Saudi Arabia), water utilities have promoted programs to expand water use efficiency, water conservation, water reuse, and other alternative supply options in efforts to mitigate water stress [8–11]. The literature underscores the importance of evaluating the energy tradeoffs of these strategies, particularly in densely populated urban areas. For instance, a multi-sector systems analysis by Bartos and Chester [12] found that water conservation policies in Arizona could reduce statewide electricity demand up to 3%. In another case study for Mumbai [13], a scenario-based approach was used to evaluate the residential water-energy nexus for achieving the Sustainable Development Goals over the time frame of 2011–2050. This study found that the interactions between water and energy during end use (i.e., a change in energy consumption prompts a change in water consumption and visa versa) significantly affected water demand and therefore, the electricity consumption for water supply and wastewater systems [13]. Another study used a cost-abatement curve method to analyze energy and water efficiency opportunities across household appliances, and found that an average U.S. household could annually save 7600 kWh of energy (electricity and natural gas) and 39,600 gallons of water if baseline appliances were replaced by energy and water-efficient appliances [14].

Quantifying the energy and emissions footprint of alternative water supply options has also been studied. A set of key performance indicators were used to compare the performance of six decentralised and three centralised water reuse configurations for the cities of San Francisco del Rincon and Purisima del Rincon in Mexico [15]. The results indicated that decentralised water reuse strategies performed the best in terms of water conservation, greenhouse gas emissions, and eutrophication indicators; however, almost negligible energy savings were reported [15]. Two studies estimated the future energy requirements of urban water management for the City of Los Angeles [16] and Los Angeles county [17]. Both studies highlighted that conservation and alternative supply options could reduce the overall energy consumed for water while an increased reliance on long-distance transfers could exacerbate future energy needs. Another study used a spatially explicit life-cycle assessment method to estimate the emissions associated with different water sources for Los Angeles and concluded that the greenhouse gas emissions footprint of water recycling could be as high as water supplied from some imported sources [18].

This paper builds on the prior literature analyzing the energy trade-offs of the City of Los Angeles's water supply portfolio by estimating the energy and emissions trade-offs of LA's future water supply trajectories through 2050 for a variety scenarios, including those that significantly increase locally sourced water supplies. We analyze how electricity demand and emissions are shifted in time and space across electricity serving utilities in California. We first provide an overview of the city's baseline water supply, as well as a series of projected business-as-usual and local water supply trajectories; second, we estimate the electricity demanded for water across the time frame extending from 2020 through 2050 and identify the main driving factors that affect water-related electricity demand for each trajectory; third, we spatially disaggregate each electricity demand estimate according to the utility delivering electricity for sourcing and/or treating each water source; and finally, we discuss the energy and emissions burden of future water supply trajectories. Our analytical framework is applied to reveal the potential tensions that could arise in efforts to simultaneously increase Southern California's local water supply, while ramping up efforts to decrease greenhouse gas mitigation strategies.

2. Water Supply System of the Los Angeles Department of Water and Power

The water supply system in Los Angeles was engineered in the early twentieth century [19,20]. The Los Angeles Department of Water and Power (LADWP) manages the City's water supply and is the second largest municipal water utility in the U.S. [21], delivering water to nearly four million people living in its service territory [7]. Approximately 560 million cubic meters of water is consumed annually by over 680,000 residential and business water service connections [21]. Much of LADWP's water supply is imported from sources outside the City, as local water supplies are limited and precipitation averages only about 12–15 inches per year [20]. Therefore, a large fraction of LADWP's water portfolio has historically been purchased from Metropolitan Water District (MWD), which pumps water hundreds of miles from the Colorado River (via Colorado River Aqueduct or CRA) and northern parts of the state through California Aqueduct in the State Water Project (SWP-East branch and SWP-West branch). In addition, the City of Los Angeles owns the gravity-fed Los Angeles Aqueduct (LAA), which conveys water from the Owens River in the Eastern Sierra Nevada Mountains to Los Angeles. These aqueducts are shown in Figure 1. During 2012–2016, these three major sources (LAA, SWP, and CRA) collectively served about 84% of LADWP's consumed water [21]. Local groundwater makes up most of the remaining supply. Recycled water in the past few years has offset some non-potable water demand (i.e., for industrial and irrigation uses). Efficiency and conservation have also been major priorities for LADWP because of the limits of its local water supply commensurate with its population. In fact, based on a comparative study [22], LA's success with conservation measures has led to constant reduction in LA's daily per person water use even to levels less than many other major cities in the U.S. and across the world. Additionally during drought periods, LADWP has used mandatory water conservation ordinances to ease water shortages [20,23].

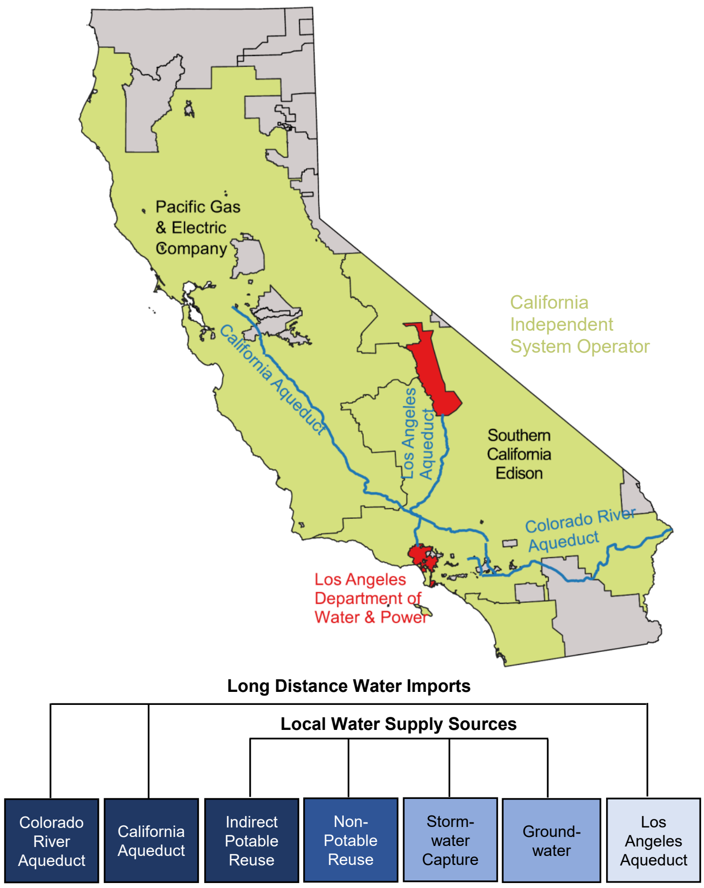

Figure 1. Water supply sources for the Los Angeles Department of Water and Power (LADWP). The areas shown in red and green represent the LADWP and the CAISO (the California Independent System Operator) regions, respectively. The color of each block in the bottom illustration represents the energy intensity of its respective water supply source, where the darkest blue corresponds to the highest energy intensity source and the lightest blue, the lowest.

For Los Angeles, a reliable water supply has been a grand challenge given the region's historical experience with multi-year drought events. Thus, the city seeks alternative sources of water to expand local water availability and to support water supply reliability. Hence, the City of Los Angeles has policy initiatives in its sustainability plan to increase the utilization of local water supplies [24]. These initiatives include:

1. Reducing average per capita potable water use by 22.5% by 2025 and 25% by 2035 compared to the baseline of 133 gallons per capita per day in 2014, as well as maintain or reduce 2035 per capita water use through 2050;
2. Reducing imported water purchases from MWD 50% by 2025 compared to the 2013–2014 fiscal year baseline;
3. Expanding all local sources of water (i.e., groundwater, recycled water, stormwater capture and conservation) to cumulatively account for 70% of the total supply by 2035;
4. Recycling 100% of all wastewater for beneficial reuse by 2035; and
5. Capturing 150,000 acre feet of stormwater, annually, by 2035.

Shifting LADWPs water portfolio will also shift the energy required for its water supply. New water recycling projects can be as energy intensive as MWD imports. (See Figure 1 for the relative energy intensities of LA's local and imported water sources.) Water recycling projects, including non-potable reuse (NPR) and indirect potable reuse (IPR) (via groundwater recharge), are important elements of Los Angeles's plan to increase local water supplies, but they have different energy needs and potential/capacity limitations. Non-potable reuse primarily offsets industrial and irrigation demands [25] (e.g., for agriculture, landscapes, parks, schools, golf courses) and, therefore has limited potential in replacing potable water demands. Furthermore, some industrial facilities have applications that require water that is of higher quality than non-potable water quality (i.e., typically tertiary-level treated) and/or might not have access to recycled water distribution networks. LADWP currently has four recycled water service areas with separate distribution networks that collectively delivered about 45 million cubic meters of NPR in fiscal year 2014/2015, from which approximately 84% was consumed for environmental uses (e.g., for dust control, seawater barriers, and other environmental uses), 14% for irrigation, and 1.6% for industrial applications [7].

IPR via groundwater recharge has higher potential in terms of offsetting urban potable water demands [26]. Requirements for indirect potable categories of recycled water use are different from NPR. IPR requires advanced treatment techniques such as microfiltration, reverse osmosis, ozone, biological activated carbon, and/or advanced oxidation that are often more energy intensive than tertiary treatment and disinfection required for NPR applications [27,28]. In addition, groundwater recharge projects need energy for pumping recycled water from its water treatment location to a groundwater spreading basin (i.e., for injecting water into groundwater aquifers), as well as for pumping water back up from an aquifer and transferring it to potable water distribution network. Since new recycling projects within LADWP's service network are still in their planning stages, there is great uncertainty about their energy footprint and water recovery rates. These factors will depend highly on regional topography, existing land use, the distance between recycled water production and spreading basins [29,30], as well as the type of treatment technology and scale of treatment capacity [31,32]. IPR has a large potential for expansion. The largest wastewater treatment plant in Los Angeles (i.e., Hyperion plant) treats about 363 million cubic meters of wastewater annually. Hyperion currently discharges nearly 83% of its treated wastewater effluent to the Pacific Ocean, which could otherwise be treated to a higher quality to produce recycled water [7]. In addition, there are three smaller wastewater treatment facilities in the city and a few others in neighboring cities that could either produce some amount of recycled water now or be retrofitted to do so. In regards to spreading ground capacity to store recycled water, one study estimated that there are about 30 existing spreading basins in the metropolitan Los Angeles region that are generally underutilized outside the winter months (i.e., approximately 12% of their theoretical infiltration capacity is used) [30].

Stormwater runoff from urban areas is another underutilized local water resource that can be used for groundwater recharge or direct use for landscape irrigation. Stormwater generally requires less intensive water treatment than water treated to IPR standards, and hence, requires less energy. Several centralized and distributed rainwater harvesting projects being pursued by LADWP are estimated to have a total volumetric potential between 163 and 178 million cubic meters by 2035 based on conservative and aggressive scenarios, respectively [7].

The trade-offs between water availability, water supply potential, and the energy requirements of different water supply sources challenge the sustainability of long-term water supply plans; thus, these trade-offs must be accounted in the decision-making process. LADWP's Urban Water Management Plan (UWMP) is a comprehensive water management planning document (mandated by the California Department of Water Resources for every urban water supplier that annually delivers over 3.7 million cubic meters (or 3000 acre-feet) of water annually, or serves more than 3000 urban connections [33]) and is updated in every five years. Although the electricity use in California's water sector is substantial, it is generally voluntary for the water agencies to report water-related energy consumption. LADWP reports information about water supply-related electricity use for historical years in its 2015 UWMP [7], and briefly describes electricity demand trajectories for its future water supply plans. However, there are no energy projections to estimate the consequences of the City of Los Angeles' latest water sustainability goals, which are not yet reflected in LADWP's UWMP. This study addresses this knowledge gap by analyzing the factors that are most likely to drive shifts in the electricity needed for future water supply options.

3. Methods

Here we develop an integrated water-energy systems framework that utilizes a top-down approach to estimate electric load projections for LADWP's water network for the reference year (average between 2010–2015) through 2050 in 5-year increments. We also propose a method to study the relative significance of key factors impacting electricity demand for the utility's evolving water supply over time. Methodological details are described in this section.

3.1. Integrated Water-Energy System Framework

A block diagram of LADWP's water supply stages is plotted in Figure 2 to illustrate the water supply system sources (inputs) and discharges (outputs) considered in this analysis. Our control volume includes the stages involved with supplying water (i.e., surface water supply and recycled water systems). Thus, wastewater management stages (i.e., wastewater collection, wastewater treatment and discharge) are excluded from study boundaries because these processes are managed by a separate entity (i.e., the Los Angeles Bureau of Sanitation), but the water cycle stages involving recycled water production (i.e., additional treatment and distribution) are included in the study as they contribute to LADWP's water supply. For each year studied, we utilize energy intensity values (EI_i in kWh/m^3 for each stage of i) and annual water supply volumes (V_j in m^3 per year) from each water source of j to calculate the total annual electricity demand for the system (E^t in kWh per year), using Equation (1):

$$E^t = \sum_i^n \sum_j^m EI_i V_j^t \tag{1}$$

The energy intensity values of the various water supplies and treatment processes applied within this framework are presented in Table 1. When available, we use EI values reflecting those received by a communication with LADWP or from LADWP's UWMP [7]; otherwise we use EI values from literature [17,34,35]. To address issues related to uncertainty in EI values, we provide electricity demand estimates based on a range of EI values that reflect values in the literature. Otherwise, when no ranges were available, we apply $\pm 20\%$ to nominal EI values. These high and low EI value bounds are noted in parentheses in Table 1.

Table 1. Energy intensities of LADWP water supply sources and electricity serving entities.

Water Supply Source	Water Stage	Electricity Supplier	EI in kWh/m3, Nominal (Low, High) [ref]	Notes
Los Angeles Aqueduct (LAA)	Conveyance	LADWP	0 [7]	LAA aqueduct is entirely gravity fed. Hydropower generation is excluded in this analysis. Water is treated at LA Aqueduct Filtration Plant (LAAFP).
	Treatment	LADWP	0.03 (0.02, 0.04) [17]	
State Water Project – West Branch (SWP – West)	Conveyance	Non-LADWP	2.09 [7] (1.7, 2.5) [1]	This water is purchased from Metropolitan Water District. This water is treated in LAAFP and Jensen Treatment Plant. EI represents the weighted average value.
	Treatment	LADWP	0.03 (0.02, 0.04) [17]	
State Water Project – East Branch (SWP – East)	Conveyance	Non-LADWP	2.6 (2.5, 3.7) [17]	This water is purchased from Metropolitan Water District. The listed energy intensity for treatment is the weighted average of the energy intensities for the Weymouth and Diemer filtration plants.
	Treatment	Non-LADWP	0.03 [7] (0.02, 0.04)[17]	
Colorado River Aqueduct (CRA)	Conveyance	Non- LADWP	1.6 [7] (1.6, 1.9) [17]	This water is purchased from Metropolitan Water District. The listed energy intensity for treatment is the weighted average of the energy intensities for the Weymouth and Diemer filtration plants.
	Treatment	Non-LADWP	0.03 [7] (0.02, 0.04) [17]	
Groundwater pumping	Extraction	LADWP	0.5 [7] (0.2, 0.5) [17]	Groundwater-well pumping energy intensity depends on factors such as water level, and pumping efficiencies. Energy use for treatment is neglected.
Captured stormwater for direct use	Collection	LADWP	0	It is assumed that distributed stormwater capture projects are mainly gravity fed with negligible energy needs. This water is used for on-site outdoor demand.
Non-potable reuse (NPR) (for irrigation and industrial use)	Treatment and distribution	LADWP	0.9 [7] (0.3, 1.1) [34] (for imported NPR, 0.5 [7] (0.4, 0.6) [1])	The assumed EI accounts for additional energy consumed for advanced treatment and for pumping to irrigation and industrial consumers. The NPR distribution network is separate from the potable water system. The EI value for NPR imports accounts only for pumping load.
Indirect potable reuse (IPR) via groundwater recharge from water recycling	Treatment	LADWP	0.6 (0.5, 0.7) [1]	It is assumed that IPR needs an advanced level of treatment. The EI values were chosen based on communication with LADWP for a potential IPR project utilizing the Hyperion wastewater treatment facility's effluent. There is uncertainty associated with these EI values because these projects have not been implemented yet.
	Conveyance and injection	LADWP	0.5 (0.4, 0.6) [1]	
	Extraction	LADWP	0.4 (0.3, 0.5) [1]	
	Conveyance	LADWP	1.5 (1.1, 2.0) [1]	
IPR via groundwater recharge from stormwater capture	Capture and transfer	LADWP	0	It is assumed that stormwater is captured and transferred to groundwater spreading basins by gravity. It is also assumed that EI values for water extraction from ground and conveyance to the water supply system are similar to those communicated by LADWP reflecting water recycling IPR projects.
	Extraction	LADWP	0.4 (0.3, 0.5) [1]	
	Conveyance	LADWP	1.5 (1.2, 1.8) [1]	
Water delivery	Distribution	LADWP	0.1 [7] (0.1, 0.2) [1]	All potable water is delivered to end users by a single central water distribution network.
Non-potable reuse (NPR) (for environmental use)	Treatment	LADWP	0.5 (0.3, 0.8) [35]	This water is treated recycled water, which is used for environmental uses. The EI value reflects the energy needs of advanced treatment with nitrification. The lower and higher values correspond to treatment capacities of 100 million and 1 million gallons per day, respectively [35]. It is assumed that this recycled water is transferred by gravity to environmental project locations.
	Transfer	LADWP	0	

[1] The lower and higher EI values are obtained by applying 20% to listed nominal EI values.

Since LADWP's imported water travels long way to arrive to the city, some of LADWP's water infrastructure, including pumping and raw water treatment, is provided electricity by other utilities. Thus, the electricity-supplier for each energy consuming water facility was determined according to its geographic location based on publicly available documents from LADWP (see Table 1). Two distinct tags (i.e., LADWP and non-LADWP) were applied to distinguish the electric loads supplied by LADWP versus those supplied by other neighboring electric utilities, typically within California Independent System Operator (CAISO).

Other assumptions were made to estimate water-related electricity demands. For example, we assumed no losses in water across each individual water supply stage; in other words, the volume of water entering each facility/stage equals the volume of water exiting that stage, which transfers to the subsequent stage that follows. However, water losses (including firefighting and mainline flushing to improve water quality) are accounted for as non-revenue generating water demands in LADWP's projected total water demand. Thus, we do not make further assumptions regarding to potable water lost to the environment. We understand that ignoring water losses may cause an overestimation of electricity demand, but given the low fractions of water losses in LADWP (the real water losses accounted for 3.8% of total supplied water in 2013/2014 [7]) and the fact that most electricity consumed for water supply occurs upstream of the water distribution system, the significance of this potential overestimation of annual electricity consumption is likely small. Additionally, we assume water leaving the treatment stage is potable and is distributed uniformly across LADWP consumers, regardless of the source or location of treatment and consumption. In terms of recycled water, we consider the marginal energy needs of treating the effluent exiting wastewater treatment facilities to meet recycled water standards, as well as the energy needed for recycled water distribution pumping [36]. We also account for the electricity needed for producing recycled water that is used for beneficial reuse (namely for environmental uses), even though this water is eventually discharged into the environment without offsetting end-use water demand.

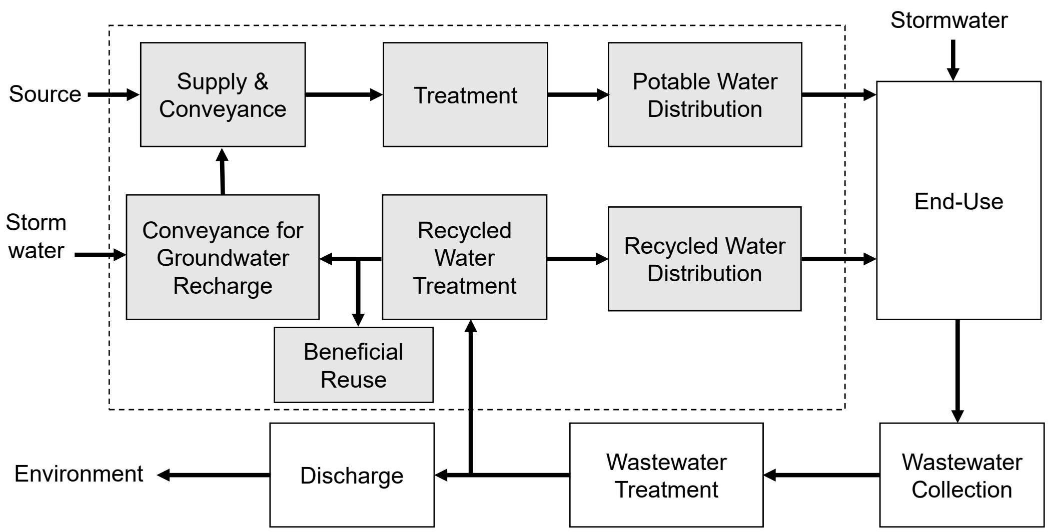

Figure 2. Block diagram of the general components of a water supply system. The dashed box indicates the boundaries of this study.

3.2. Scenario Definitions

Scenarios are developed to explore the energetic tradeoffs of increasing local water supplies over 5-year increments for years spanning 2020 through 2050. We define two scenarios for average weather year conditions (S1, S2), and two additional scenarios (S3, S4) to simulate future water supplies in a single dry year (that assume similar hydrology to 2014/2015), as a proxy for future possible droughts. In these scenarios, S1 and S3 reflect LADWP's most recent water portfolio trajectory from 2020 to 2040 in the utility's 2015 UWMP [7]; however, we extrapolate projections for years of 2045 and 2050. S2 and S4 are developed to simulate a more aggressive local water supply portfolio to represent the newer water policy targets of the Los Angeles City's Green New Deal, which are not reflected in the 2015 UWMP [24]. The scenarios are described in Table 2.

Table 2. Description of scenarios analyzed in this study.

Weather	#	Water Conservation	Water Recycling	Stormwater Capture
Average weather year	S1	Based on assumptions from the LADWP 2015 UWMP [7]	Based on LADWP 2015 UWMP [7]	Based on LADWP 2015 UWMP [7]
	S2	Maximum cost-effective potential based on LADWP water conservation study [37]	Additional recycling from Hyperion wastewater treatment plant	Aggressive potential based on [38]
Single dry year	S3	Based on LADWP 2015 UWMP for single dry year [7]	Based on LADWP 2015 UWMP for single dry year [7]	Based on LADWP 2015 UWMP for single dry year [7]
	S4	Maximum cost-effective potential [37], plus drought-related additional savings	Additional recycling from Hyperion wastewater treatment plant	Conservative potential based on [38]

For S2, we consider the maximum cost-effective conservation potential reported in LADWP's water conservation potential study [37] for the years spanning 2020 and 2035, and we assumed 2% additional conservation for each subsequent five year block thereafter (i.e., for 2040, 2045 and 2050). (Based on LADWP's water conservation potential study [37], cost-effective conservation is defined as the level of water savings achievable through cost-effective conservation programs implemented by LADWP, but it would require customer engagement through expanded financial incentives.) For S4, we assume that water savings in dry years exceed conservation volumes in average weather years due to factors such as more aggressive voluntary and involuntary conservation measures and other water saving ordinances. For stormwater, the cumulative centralized stormwater capture potential reflects LADWP's stormwater capture master plan [38]. To meet the City of Los Angeles' 100% wastewater recycling goal [24], we assume that 60% of the current volume of discharged effluent from wastewater treatment facilities will be further treated according to IPR standards for future groundwater recharge projects by 2035. The remaining 40% is assumed to be treated for environmental use. We exclude any potential water supply from seawater desalination, as LADWP does not include desalinated seawater as part of its future water portfolio [7,16]. Water demand volumes are kept constant in each set of scenarios, such that S1–S2 and S3–S4 reflect water demand volumes in LADWP's 2015 UWMP for an average year and single-dry year, respectively [7]. Figure 3 illustrates LADWP's water portfolio for a historical average year (i.e., ref.), as well as the assumed water portfolios for S1–S4.

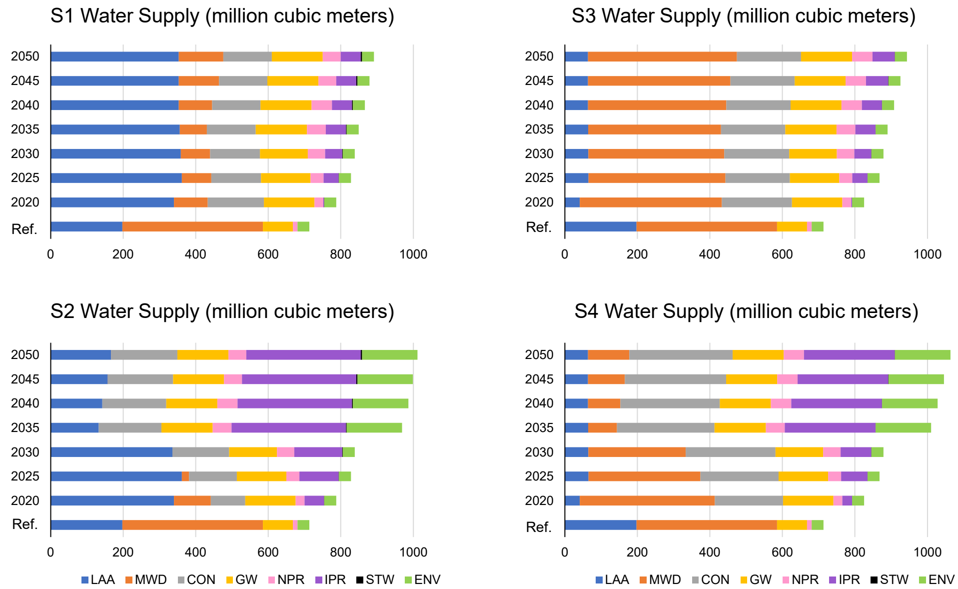

Figure 3. Historical reference year and projected water supply portfolios in S1–S4. Water supplies from LAA (Los Angeles Aqueduct), MWD (Metropolitan Water District), CON (conservation), GW (groundwater), IPR (indirect potable reuse), NPR (non-potable reuse) and STW (stormwater capture for direct use) balance LADWP's historical or projected water demand, and ENV includes recycled water that goes into environmental services.

3.3. Performance Indicators

The percentage of local water supply is defined as the fraction of water demand that is met by cumulative supplies from groundwater, stormwater capture, NPR, IPR, and future conservation. For the projection years (i.e., 2020–2050), volumes of conserved water are included in local water supply percentage calculations because the projected demand for future years does not account for future conservation measures. However, the historical average year is an exception where the water demand value is based on real water consumption data, and therefore, the local water percentage excludes conservation.

Daily water use per person (in the units of liters per person per day, $L/P/D$) is used as an indicator for water demand (note that water demand excludes volume of water for beneficial reuse). Two energy indicators are defined, one to capture the electricity demand intensity of the water system in kWh/m^3, and the other to track annual electricity demand for water supply per person in kWh/P.

We also estimate emissions per unit of water demand in $kgCO_2/m^3$. Total carbon dioxide emissions are estimated using an emissions intensity of 225 $kgCO_2$/MWh, which represents California's 2018 electric grid [39], and 75 $kgCO_2$/MWh, which was applied as a proxy for a future decarbonized grid mix based on [40]. For a future decarbonized grid in 2035, we calculated the average emissions intensity of California's electricity system based on information provided in [40] for the electricity generation fuel mix and total CO_2 emissions in 2030 and 2040. For the state of California to achieve an 80% reduction in California's greenhouse gas emissions by 2050 (from the 1990 levels), the high electrification pathway assumes that the share of renewable energy sources in California's electricity supply is 60% and 79% in 2030 and 2040, respectively [40], which illustrates significant growth from the share of renewables in 2018, i.e., 29% based on [39].

3.4. Decomposing Driving Factors for Electricity Demand

An index decomposition analysis (IDA) is formulated to examine the impact and significance of key factors influencing the electricity demand for LADWP's water system over time. We define influencing factors, including population, water use (influenced by water demand and water conservation programs), and the energy intensity of water supply portfolios. We reformulate Equation (2) to describe the relationship between the three predefined influencing factors and the total electricity demand for the water system:

$$E^t = P^t \times \frac{V^t}{P^t} \times \frac{E^t}{V^t} = P^t \times \frac{V^t}{P^t} \times EI^t = P^t \times \frac{V^t}{P^t} \times V^t \sum_i^n \sum_j^m EI_{i,j} v_j^t \quad (2)$$

where E^t is electricity demand for water, P^t is population, V^t is volume of water supplied (water supplied is equal to projected water demand minus projected conservation), v_j^t is the fraction of water supplied from source j in year t, $EI_{i,j}$ is energy intensity of water supplied from source j in water supply stage i. A change over time in electricity demand can be decomposed into three driving factors relating to the effects of population, physical water supplied per person, and the energy intensity of water supply as it is shown in Equation (3). Here, we apply the most common decomposition method, i.e., additive logarithmic mean Divisia index method I, from [41], to calculate ΔE_P, ΔE_V and ΔE_{EI} shown in Equations (4)–(6), where $L(x, y) = (x - y)/(lnx - lny)$ for $x \neq y$, and $L(x, y) = x$ for $x = y$. We conduct decomposition analysis of total electricity demand change in year 2035 and the reference historical average ($\Delta E = E^{t=2035} - E^{Ref}$), and we repeat the analysis for all four studied scenarios.

$$\Delta E = \Delta E_P + \Delta E_V + \Delta E_{EI} \quad (3)$$

$$\Delta E_P = L(E^t, E^{Ref}) \times ln(P^t / P^{Ref}) \quad (4)$$

$$\Delta E_V = L(E^t, E^{Ref}) \times ln((V^t / P^t)/(V^{Ref} / P^{Ref})) \quad (5)$$

$$\Delta E_{EI} = L(E^t, E^{Ref}) \times ln(EI^t / EI^{Ref}) \quad (6)$$

4. Results

4.1. Electricity Demand

Average annual electricity demand estimates for LADWP's water system from 2020 to 2050 for each scenario are presented in Table 3. For all four scenarios, electricity demand slowly grows over time in almost all projected years between 2020 and 2050. Between 2020–2030, S1 and S2 show a lower electricity demand for water compared to the historical average year. In period between 2035 to 2050, S1 continues to be less energy intensive than the historical average while S2 results in a jump in electricity demand in 2035 due to the large expansion of the IPR supply. The dry weather scenarios (S3 and S4) have higher energy requirements compared to the historical average in almost all studied years, but scenario (S4) has lower electricity demand growth compared to LADWP's 2015 UWMP scenario (S3). In the short-term, electricity demand for S3 and S4 is close to the historical average year while over the long-term, much higher electricity demand is observed. Long-term electricity demand for aggressive local water supply scenarios (i.e., S2, S4) are close in magnitude, despite their differences in hydrology conditions.

More details about the electricity demand and carbon dioxide emissions are presented for the year 2035 in Table 4. The year 2035 is chosen because most water targets are set for that year in the Los Angeles City's Green New Deal plan [24]. Less energy-intensive supplies in S1, such as stormwater capture and aggressive water conservation, reduce water demand and offset energy-intensive MWD imports, such that electricity demand for water in 2035 in this scenario is lower compared to the historical average. By contrast, the S2 aggressive local water supply case in 2035 has total energy requirements that are moderately higher than the historical average (16%). In other words, there are neither significant energy penalties nor energy savings for adopting an aggressive local water supply system. Accordingly, replacing the water pumping loads associated with importing water from MWD, with the energy demands of advanced treatment and pumping, for local water recycling results in a nearly equivalent overall energy footprint. However, the distribution of who provides this electricity for the water supply in each respective scenario changes substantially, and thus has important implications for electric utilities across California. In the high local water supply scenario (S2), water-related electricity provided by LADWP increases over 6 times (from 180 in historical reference year to 1100 GWh in 2035), such that the electricity demand for water grows from approximately 0.8% of total LA's system load in the historical average year to 4% in 2035. At the same time, the electricity that would have otherwise had to be delivered to water pumping infrastructure outside of LADWP's electricity service territory is dramatically reduced as energy intensive imports from Northern California and the Colorado River decrease. Thus, although the amount of electricity consumed in the reference case versus the high local supply case (S2) is similar, the relative fraction of electricity delivered by electric utilities (i.e., LADWP versus other Investor-Owned Utilities in CAISO) shifts dramatically with large electricity demand growth implications for LADWP. While the decarbonized future electric grid significantly reduces the emissions associated with electricity consumption by definition, our analysis indicates that growing water-related electricity demand served by LADWP can increase the total amount of carbon dioxide emissions associated with LADWP's water supply, even with a cleaner future electric grid. But total water-related emissions (i.e., considering the emissions associated with LADWP, as well as other utilities in CAISO) will likely decrease by 2035 compared to historical reference in average weather scenarios because of grid decarbonization.

Table 3. Average total annual electricity demand for LADWP's water supply for the historical reference and projection years between 2020 and 2050 for S1-S4 scenarios. All values are in GWh and are rounded to two significant digits.

Scenario	Ref. Year	Year 2020	Year 2025	Year 2030	Year 2035	Year 2040	Year 2045	Year 2050
S1	780–1200	280–470	370–600	380–620	390–630	420–680	450–730	470–760
S2	780–1200	410–600	390–570	400–580	900–1300	900–1300	900–1300	900–1300
S3	780–1200	790–1200	870–1300	880–1300	880–1400	900–1400	950–1400	980–1500
S4	780–1200	810–1300	800–1400	760–1400	830–2000	850–2000	870–2100	890–2100

Table 4. Annual electrical electricity demand and CO_2 emissions for the reference year and 2035 projections for all four studies scenarios. Note that percentages of water-related electricity demand, calculated in reference to total electricity demands in LADWP and CAISO regions, are calculated based on LADWP's 2017 Retail Electric Sales and Demand Forecast [42] and CAISO demand projections reported in California Energy Demand 2018–2030 Revised Forecast [43], respectively. Electricity demand and emissions values are rounded to two significant digits.

Scenario	Total		LADWP			Outside LADWP		
	Average Electricity Demand (GWh)	CO_2 Emissions (1000 Tonnes)	Average Electricity Demand (GWh)	% LADWP Electric Load	CO_2 Emissions (1000 Tonnes)	Average Electricity Demand (GWh)	% CAISO Electric Load [1]	CO_2 Emissions (1000 Tonnes)
Ref.	970	220	180	0.8%	40	790	0.4%	180
S1 (2035)	530	40–120	380	1%	28–85	150	0.1%	12–35
S2 (2035)	1100	80–250	1100	4%	84–250	0	0%	0–0.1
S3 (2035)	1100	85–250	380	1%	28–85	750	0.3%	56–170
S4 (2035)	1100	80–240	910	3%	68–200	160	0.1%	12–37

[1] We applied an average annual growth rate of 0.84% to CAISO total electricity demand forecast for year 2030 in [43] to estimate total electricity demand for 2035.

The dry year scenarios, S3 and S4, have higher energy needs than the average weather year scenarios due to the limited availability of water from LAA that requires no energy for pumping (which is accommodated by a higher reliance on water supplies from energy-intensive sources). The aggressive water conservation programs implemented in S4 reduced overall water supply needs compared to S3 and hence had lower electricity demands. Considerable amounts of energy were consumed in both S3 and S4 to import water from outside LADWP (i.e., from pumping projects served by Investor Owned Utilities in the CAISO region), but significant electricity demands also occur within LADWP due to increased supply from recycling. Therefore, for S3 and S4 in contrast with S1 and S2, we see a more distributed burden of energy among CAISO and LADWP regions. Higher water-related carbon dioxide emissions are expected for S3 and S4 than S1 but approximately similar to S2. The magnitude of total emissions in S3 and S4 can be lower than historical average if the electric grid decarbonizes significantly by 2035.

4.2. Main Drivers for Electrical Energy Demand

The relationship and relative impact of population growth, water conservation, and water supply mix on electricity demand in the year 2035 is compared to the historical average in Figure 4. This IDA analysis suggests that shifting the water supply portfolio from a more energy intensive system, on average, to a lower energy intensive system is the main driving factor for reducing energy consumption in S1 compared to the reference year. By contrast, transitioning to a water supply mix with more local water supplies in S2 leads to only a slight increase in electricity demand, which means that the average energy intensity of the water supply system in 2035 is slightly increased from the reference historical average. In S1 and S3, the impact of water conservation on reducing electricity demand for water is almost similar to the impact of population growth. In S2 and S4, however, aggressive conservation exceeds the impact of population growth on electricity demand for water. In S3 and S4, electricity demand is slightly higher than the historical average, due to combined effects of aggressive conservation and a shift to more energy-intensive water sources.

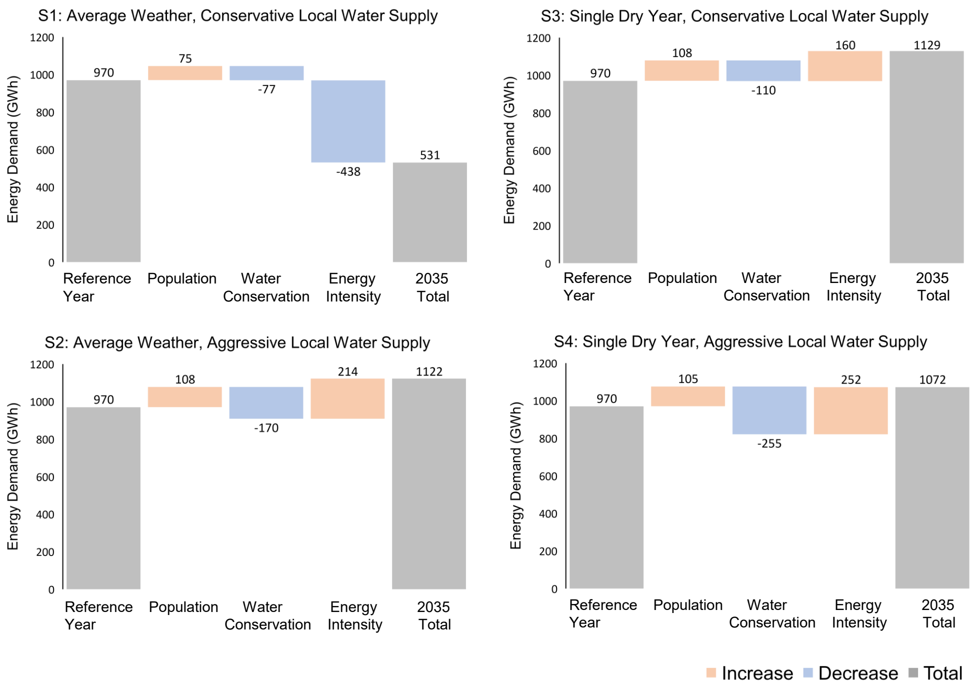

Figure 4. Driving factors for electricity demand changes in 2035 versus the historical average reference year for the four studied water supply scenarios for LADWP.

4.3. Scenario Performance Indicators

Three performance indicators of total annual water-related electricity demand per person in LADWP, annual water use per person per day in LADWP and total electricity demand intensity of water supply (including electricity provided by LADWP and other electric utilities) are illustrated in Figure 5 from the historical reference year to 2020–2050 trajectories. The results show that annual water-related electricity demand per person across all years for LADWP's future water supply scenarios ranges between 98 and 269 kWh/person, with lower values for S1. In fact, the long-term annual electricity demand per person values for S2, S3 and S4 are close to the historical average value (247 kWh/person per year). In all scenarios, whether assuming a dry year or average weather year, the daily water use per person is expected to be lower in all projection years than the historical per person daily water use (475 L/P/D) (due to water conservation assumptions). The large difference between daily water use per person between S2 and S4 is due to the additional conservation that was projected for a future dry weather. The wedges in Figure 5 show the total electricity demand intensity of water supply system. The electricity demand intensity of the water supply system is relatively higher for S2, S3 and S4 (between 1.5 and 2 kWh/m^3) as compared to S1 (between 0.5 to 1 kWh/m^3). The total electricity demand intensity value estimates are comparable to the range of energy intensities reported by Porse et al. [17] as 1.44–1.51 kWh/m^3 and Sanders [16] as 0.53–2.03 kWh/m^3 for average weather condition in 2034/2035.

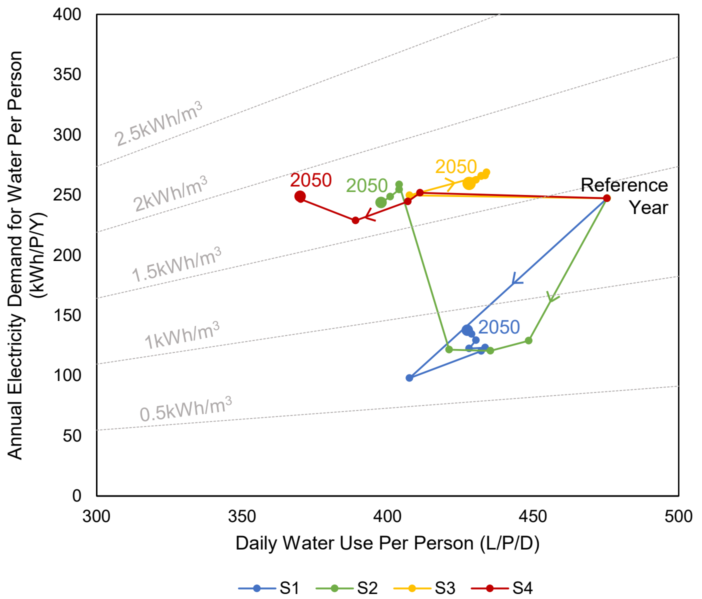

Figure 5. Annual electricity demand per person versus water use per person per day for the studied water supply scenarios for LADWP. The wedges indicate the total electricity demand intensity of water supply system.

5. Discussion

5.1. Energy Trade-Offs of Local Water Supply Options

As water sources dependent on snowpack are vulnerable to drought (e.g., water imports from the Sierra Nevada and the Colorado River), there are large benefits to expanding local water supplies, such as stormwater and recycled water, for mitigating against water shortages during drought. However, increasing recycled water supplies that are treated to potable water quality standards have electricity demand ramifications. Treating water to the quality acceptable for IPR (for groundwater recharge) is generally more energy intensive than treating surface water supplied from distant sources [16], and therefore, there might not be considerable benefits in terms of overall electricity demand for water, and in some cases there may actually be overall energy increases as water recycling projects may need extensive pumping in addition to treatment [6]. In our analysis, we assumed large groundwater recharge projects will be implemented by 2035 in the S2 scenario, when the local water supply percentage will increase substantially at the cost of increased electricity demand in 2035 compared to the previous projection year 2030.

Water demand management strategies, namely water conservation, also have energy impacts. Saving water saves energy that would otherwise be consumed to supply the amount of water saved.

The energy savings associated with each unit of saved water is not equal given LADWP's diverse water portfolio. To reflect LADWP's goals for managing its water supply portfolio over time, we made an underlying assumption that water supply is prioritized from local sources first (which are limited by factors such as treatment and distribution infrastructure for water recycling), then water imports from LAA (which are limited by environmental regulations and hydrology conditions), followed by imports from MWD. Hence, the energy savings of water conservation depends on the marginal supply source that conservation is otherwise avoiding. In this sense, the energy benefits of water conservation are equal to the energy that would otherwise be used importing from MWD, when these water supplies are the marginal source. After the need for MWD purchases is eliminated, the LAA supply becomes the next marginal imported water source, and therefore, the further reduction in water use has lower energy benefits since water from LAA is the least energy intensive source. In other words, the energy benefits of saving water is higher when imports of water from SWP and CRA are the water volumes being displaced, compared to the case in which LAA water is the only source of water imports (i.e., in S2).

Water conservation strategies are not just important for drought resiliency. In lieu of expected growth in population, a continuous commitment to conservation programs is necessary to maintain or even decrease daily per person water use volumes further. Water conservation strategies are not just important for drought resiliency. In lieu of expected growth in population, a continuous commitment to conservation programs is necessary to maintain or even decrease daily per person water use volumes further. Our decomposition analysis suggests that conservation in the average weather scenarios (i.e., S1 and S2) also tends to mitigate increases in energy for water that are driven by higher water demand projections in the year 2035 (compared to the historical average year).

5.2. Spatial Shift in Electricity Demand for Water

Increasing the usage of local water sources in Southern California (and reducing imports from large pumping projects) will cause a dramatic shift in the locations where the water-related electricity demands occur across the state (see Table 3). The large pumping energy requirements of conveying water from the SWP and CRA mostly occur in regions outside of LADWP's electricity service territory; hence, reducing those imports translates in reductions in energy usage by CAISO investor owned utilities including Pacific Gas and Electric and Southern California Edison. On the other hand, the energy loads incurred from the pumping and treatment of local water sources, including groundwater, stromwater and water recycling, are majorly located within LADWP's electricity service territory. Accordingly, moving away from MWD imports and towards local supply sources will shift the energy footprint of water from outside the city into LADWP region. Our spatial disaggregation of electricity demand reveals that transitioning to a local water supply might vastly decrease the electricity demand for LADWP's water supply in the CAISO region. This shift in electricity demand might increase the percentage share of water-related electricity demand from LADWP's total system load from 0.8% in the reference year to about 4% in 2035. This increase in electric load is equivalent to the annual electricity use of over 22,000 average households in California (based on data from [44]). This additional electricity demand in the city will add to its carbon footprint and other upstream environmental externalities associated with electricity generation under current electric grid conditions (although the externalites associated with decreased CAISO generation would be reduced in other regions). The magnitude of environmental externalities will depend on the success of decarbonizing the energy system by moving away from coal and natural gas fuels towards cleaner sources of energy. If the energy transition happens fast enough, the increased electricity demand for water might be insignificant in terms of its carbon footprint. However, with the current electric grid fuel mix, the city's water-related emissions will increase dramatically when aggressive local water supply plans are implemented.

5.3. Achieving Water-Related Sustainability Targets

For comparison, the performance indicators calculated for all four scenarios are summarized in Table 5. The estimated ranges of electricity demand intensity values in 2035 for S1 are lower than the reference historical average, while the other three scenarios show either a similar or a higher range. The emissions intensity of water depends on the assumed average emissions factor of the future electric grid and the electricity demand intensity of the water supply mix. The combination of these two factors show that the emissions intensity could be much lower for a cleaner grid; however, under the current electric grid fuel mix, the emissions intensity of water could be higher in S2–S4 than the historical value (0.3 $kgCO_2/m^3$).

Comparing the performance of studied scenarios with the water targets of the Los Angeles City plan [24] highlights a few points:

- Reducing water purchases from MWD by 50% by the end of 2025 is achievable provided that weather conditions stay normal (S1 and S2). However, even under the aggressive local water supply scenario (S4) in a dry year, achieving this water supply target remains unreachable if the expansion of local water supply is delayed until 2035.
- Supplying 70% of LADWP's water from local resources by 2035 is more likely to be achieved with a more aggressive local water supply expansion (S2 and S4) compared to LADWP's 2015 plans (S1 and S3) that requires unlocking substantial conservation and water recycling potential.
- The 2035 water use per person per day target will be difficult to realize under LADWP's 2015 UWMP, and therefore, will require water savings in addition to reaching its cost-effective conservation potential. With aggressive conservation, LADWP's per person daily water use can position the city among other large cities such as Toronto, Sydney and Melbourne that historically had daily per person water use values lower than LADWP (in the range of 250–435 L/P/D) [22].

Table 5. Summary of performance of studied scenarios in achieving LA's sustainability targets, as well as electricity demand intensity and emissions intensity of water for year 2035 of each scenario.

LA's Green New Deal Targets					
Indicator	**Target [24]**	**S1**	**S2**	**S3**	**S4**
Reduction in MWD imports by 2025	50%	83%	96%	21%	36%
% Local Supply by 2035	70%	47%	84%	50%	83%
Per Capita Water Use by 2035 (L/P/D)	379	428	404	428	370
Electricity Demand and CO_2 Footprint					
Indicator	**Ref. Year**	**S1 (2035)**	**S2 (2035)**	**S3 (2035)**	**S4 (2035)**
Electricity Demand Intensity (kWh/m^3)	1.1–1.7	0.6–0.9	1.4–2.0	1.3–2.0	1.4–3.4
CO_2 Intensity ($kgCO_2/m^3$) [1]	0.3	0.06–0.2	0.1–0.4	0.1–0.4	0.1–0.4

[1] For the reference year, the value is calculated only based on emissions intensity of California's 2018 electric grid; therefore, no range is provided. The other ranges use two different emissions intensities that are applied to average electricity demand estimates (i.e., 225 and 75 $kgCO_2/MWh$ representing California's 2018 [39] and a future decarbonized electric grid [40], respectively).

5.4. Policy and Planning Implications

The results of this study demonstrate important implications for urban system planning with broader sustainability objectives. The case study of LADWP shows that water policies intended to increase the sustainability and resilience of its water system can be energy intensive and burden its electricity system, thus challenging other sustainability objectives such as greenhouse gas mitigation. Extensive coordination between the water and energy sectors is needed, so that transitions in the energy and water systems facilitate short-term and long-term sustainability priorities without exacerbating tensions between the two sectors.

We recommend that the energy trajectories of future water supply portfolios be incorporated into the city's long-term planning to facilitate holistic decision-making in regards to electricity demand planning, drought resiliency considerations, and ecosystem protections. Synergistic opportunities in water and energy systems open new areas of innovative solutions such as improving the energy efficiency of operations, coordination of water pumping operations with water storage, resource recovery, on-site energy generation, technological innovations, and water trading schemes that could benefit both water and energy sectors, and could reduce the energy needs of water systems [45–51]. Future water systems should be designed based on holistic systems' paradigms that are multipurpose and integrative to promote reliability, resilience and sustainability for the city's urban water system.

6. Conclusions

In this paper, we assess a set of future water supply scenarios for LADWP, which markedly increase local water sources including water recycling, stormwater capture, and conservation in order to support reliable and resilient water supply. We evaluate these scenarios as possible pathways for achieving the city's sustainability water targets using indicators to track the performance of each scenario in terms of electricity demand per unit of water, emissions per unit of water, daily water use per person, and annual electricity demand per person. We estimate the energy requirements for adopting each new water portfolio through 2050 and find that major shifts in water supply sources (i.e., from imports to local supplies) might not significantly change overall energy requirements, but they will change the distribution of the water-related electric load for LADWP's electricity balancing area and other electric load serving entities. Expanding groundwater recharge projects will add additional electric demands on LADWP's electricity system that could be more than 6 times the historical water supply-related electricity demand of LADWP's territory. By contrast, non-LADWP electric load serving entities will likely experience lower electricity demands due to reduced water imports that are transferred over long distances from the city. The decomposition analysis concludes that aggressive conservation measures are important to offset the growth in water demand and the effects of population increases, but the total electricity demand intensity of the water supply has the highest impact on the energy requirements of the water sector in most scenarios.

Our results emphasize that if the City's local water supply adoption occurs at a faster rate than its decarbonization goals in the power sector, those water policies might cause an interim increase in greenhouse gas emissions across LADWP's service territory (due to the increased electricity demand for water) which will be in conflict with the City's goals for mitigating future greenhouse gas emissions. Moreover, this potential growth in electricity demand within LADWP's network might increase other environmental externalities from power generators serving the utility (e.g., increased air pollution and cooling water needs), while non-LADWP regions might benefit environmentally from reduced electricity generation. Thus, evaluating the electricity demands associated with the expansion of a more drought resilient local water supply is important to meeting the multi-faceted sustainability goals of the city, especially those related to clean energy systems.

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