Title

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Permalink

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Journal

Environmental Research Letters, 15(11)

ISSN

1748-9318

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Publication Date

2020-11-01

DOI

10.1088/1748-9326/abb9de

Environmental Research Letters

LETTER • OPEN ACCESS

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To cite this article: Edward S Spang *et al* 2020 *Environ. Res. Lett.* **15** 114031

IOP Publishing Environ. Res. Lett. 15 (2020) 114031 https://doi.org/10.1088/1748-9326/abb9de

Environmental Research Letters

RECEIVED
15 June 2020

REVISED
2 September 2020

ACCEPTED FOR PUBLICATION
18 September 2020

PUBLISHED
26 October 2020

LETTER

The cost-effectiveness of energy savings through water conservation: a utility-scale assessment

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Keywords: energy intensity, water-energy nexus, water conservation, California

Supplementary material for this article is available online

Abstract

It is well-established that water infrastructure systems require energy to treat and deliver water to end-users. This fundamental relationship presents an opportunity to secure energy savings through water conservation. In a previous study, the energy savings linked to a statewide water conservation mandate in California were found comparable in both resource savings as well as cost-effectiveness to the energy savings achieved directly through energy efficiency programs. This study pursues a similar line of inquiry, but at the scale of an individual city as opposed to a statewide assessment. Los Angeles, California, serves as the case study for estimating the energy savings secured through water conservation programs relative to energy efficiency (EE) programs enacted in the study region. We apply three different estimates of energy intensity (EI) for the conversion of water savings to energy savings. These applied EI scenarios are differentiated by scale and system boundary, including: a direct assessment of EI within the water utility service territory, an expanded boundary that includes imported water infrastructure systems, and a broader, top-down estimate for the regional hydrologic zone. Across all scenarios, the estimated energy savings secured through water conservation programs prove to be cost-competitive with the energy efficiency programs enacted by the utility. When using estimates of EI with expanded system boundaries that include the upstream energy embedded in imported water supplies, water conservation becomes a significantly more attractive pathway for saving energy. This outcome underlines the importance of clearly defining the water-energy system boundary of interest, both to determine an accurate EI value, and subsequently, to design and implement cost-effective programs that jointly conserve both water and energy resources.

1. Introduction

Energy is an integral input to the operation of water infrastructure systems. Energy is required to deliver safe and reliable water resources from source to consumer, as well as to collect and treat wastewater before discharge (Sanders and Webber 2012, Spang and Loge 2015, Chini and Stillwell 2018). This connection between water and energy resources presents an opportunity to secure real savings in energy consumption and linked greenhouse gas (GHG) emissions through water conservation programs (Spang *et al* 2018).

The water-energy relationship is especially important in California, where roughly 20% of statewide electricity and 30% of non-power plant natural gas is consumed to move, treat, and heat water across the full water life cycle (Klein *et al* 2005). Meanwhile, California has committed to significant goals to advance energy efficiency (EE) and GHG abatement statewide. The Clean Energy and Pollution Reduction Act of 2015 (Senate Bill 350 or SB350) established a target of doubling statewide EE savings by 2030 (SB350 2015) and the Global Warming Solutions Act of 2006 (Assembly Bill 32) requires the State

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to reduce its GHG emissions to 1990 levels by 2020 (AB32 2006). Further, California's arid climate and susceptibility to drought, make water conservation programs an additional priority concern for the State. In fact, the recent drought of 2014–2017 led to the first ever statewide water conservation requirement. Under Executive Order B-29-2015, Governor Brown required that all urban water agencies must collectively reduce water consumption by 25% below 2013 levels (Brown 2015). In sum, California provides a unique hydrologic and policy landscape for exploring the potential to leverage water savings to secure concurrent reductions in energy use and GHG emissions.

Previous research examined this topic at the statewide scale and estimated both the energy savings and GHG emissions reductions from the water savings mandated under Executive Order B-29-15 (Spang *et al* 2018). Not only were these savings significant from a volumetric perspective, but the analysis suggested that these savings were cost-competitive with existing EE and GHG reduction programs. However, to produce statewide results, the estimation required using high-level, regional estimates of the energy intensity (EI) for urban water provision. More specifically, the study relied on a previous report that consolidated EI by type of source water for each of the 10 hydrologic zones across the state (Navigant 2015a). However, previous studies have shown that EI can vary significantly between water agencies (Kenway *et al* 2015, Chini *et al* 2016, Chini and Stillwell 2018, Sowby and Burian 2018) and even within a single water agency based on the layout and topography of the distribution system as well as seasonal changes in demand (Spang and Loge 2015, Finley and Basu 2020). In addition to the natural variation in the EI of water systems based on location and scale, EI is also heavily influenced by the definition of the water system boundary (Kenway *et al* 2015, Porse *et al* 2020), including the inclusion/exclusion of regional water conveyance, local water utility infrastructure, water end-uses (e.g. residential, commercial, and industrial end users), and/or wastewater utility infrastructure.

Previous studies have also addressed the cost-effectiveness of linked water-energy savings. One study estimated the household water and energy cost savings (both direct and indirect) from residential appliance and fixture replacements in three major cities (Los Angeles, Chicago, and New York) by calculating cost abatement curves for each technology retrofit (Chini *et al* 2016). A pair of related studies looked at 10 water utilities in California and estimated the direct residential water, energy, and cost savings for both technological and behavioral water conservation interventions (Escriva-Bou *et al* 2015a); and, determined the optimal interventions to reduce residential utility bills in the context of water and energy price shocks (Escriva-Bou *et al* 2015b).

This study contributes to this research area by applying three distinct system boundaries to the estimation of EI values for a single urban water utility, including: a direct assessment of EI within the water utility service territory; an expanded boundary that includes water conveyance infrastructure; and, the broader, top-down estimate for the regional hydrologic zone. The EI for wastewater service provision in the study region is also included. The EI related to water end uses is not included in this study. We then apply these three distinct estimates of EI to assess the cost-effectiveness of securing water- and wastewater-derived energy savings through water conservation relative to existing EE programs deployed by the utility. The cost-effectiveness comparison is based on a calculation of cost per kilowatt-hour (US$/kWh) saved over the lifetime of each energy saving pathway included in the analysis, also known as the levelized cost of saved energy (LCSE).

The water utility for our case study is the Los Angeles Department of Water and Power (LADWP) and the wastewater utility is the Los Angeles Sanitation and Environment (LASAN). The embedded energy of the water and wastewater systems in Los Angeles has been examined in this region before, though with different aims than those presented in this paper (Chini *et al* 2016; Fang *et al* 2015, Sanders 2016, Porse *et al* 2020). Porse *et al* (2020) recently presented a novel model that integrates energy use by both water utilities and households in the larger LA County region (covering more than 100 water agencies) to explore the influence of a range of water sourcing and conservation scenarios on energy consumption and energy intensity. Sanders (2016) estimated the embedded energy of LADWP water supplies with an emphasis on understanding the energy implications of forecasted water supplies and management strategies. Fang *et al* (2015) published a comparative case study of the energy and GHG footprints for both LADWP and the Inland Empire Utility Agency with an emphasis on life-cycle-based and spatially disaggregated GHG emissions factors for water provision. While all of these studies contribute useful perspectives on the embedded energy of Los Angeles' water and wastewater systems, our approach is unique in its focus on the cost-effectiveness of the energy savings achieved through water conservation relative to existing energy efficiency programs in the context of varying system boundaries of the regional water infrastructure system.

2. Methods

To understand the influence of EI estimation approaches on the calculation of projected energy savings from water conservation programs (and their cost-effectiveness), we took a three-step approach. The first step was to consolidate the EI estimates for LADWP water provision differentiated by the three distinct system boundaries: the direct water utility service territory; an expanded boundary that includes inter-basin water conveyance systems; and, the regional hydrologic zone. We included two EI estimates of LASAN wastewater collection and treatment: values calculated directly from data provided by LASAN and estimates by hydrologic zone (Navigant 2015a). The second step involved collecting and consolidating information on the estimated cost and performance of all the water conservation programs implemented by LADWP from 2010–2015. Then, using our LADWP and LASAN EI estimates from step one, we convert the water savings to estimated energy savings for each intervention. The energy savings from the water conservation programs are then compared to energy savings secured directly through EE programs enacted within the same time period by LADWP. Finally, in our third step, we compare the cost-effectiveness of achieving energy savings through water conservation to EE program savings in terms of LCSE.

2.1. Energy intensity (EI) estimates

Energy intensity (EI) represents the amount of energy embedded within a volumetric unit of water (e.g. represented by kilowatt-hours per million gallons, or kWh/MG). When EI is estimated for water utilities, it generally includes the energy required to extract, treat, and deliver water from source to end user. For wastewater systems, where the energy inputs for wastewater collection and treatment are calculated per unit wastewater for the system (also kWh/MG). EI may also be estimated for end uses of water (e.g. residential hot water heaters) as well, however this was beyond the scope of this study.

We estimate EI for the LADWP water system at three different scales that determine the basis for three different EI scenarios utilized in our cost-effectiveness analysis. The first scenario (EI1) is based on the direct assessment of energy consumption by all LADWP water infrastructure assets (groundwater pumps, distribution pumps, and water treatment facilities) that are located within the LADWP service territory (figure 1(a)). This system boundary is useful for identifying the energy savings that will accrue directly to LADWP as a result of water conservation, since they directly provide the electricity to the water infrastructure assets in their service territory.

The system boundary for EI2 extends from the LADWP service territory to include all the water conveyance infrastructure that delivers imported water from distant locations to LADWP (figure 1(b)), including the State Water Project (SWP), the Los Angeles Aqueduct (LAA), and the Colorado River Aqueduct (CRA). The SWP and CRA are net energy consumers as conveyance in these systems requires a series of pump stations to deliver water to the LA basin, from the Sacramento River in Northern California for the SWP and from Lake Havasu in Arizona for the CRA. The LAA is a net energy producer as the water flows by gravity from the Owens Valley to LA, passing through a series of hydropower stations along the way. It is worth noting that the energy savings associated with reduced water conveyance may accrue to energy retailers other than LADWP (e.g. reduced pumping by the SWP may save electricity for Pacific Gas & Electric in Northern California and for Southern California Edison in the region surrounding LADWP in the southern part of the State).

EI3 represents an alternative regional approach that leverages existing EI values for all 10 hydrologic zones in California (figure 1(c)) from an assessment developed for the California Public Utilities Commission (CPUC) water-energy program (Navigant 2015b). This third estimate is not specific to individual water agencies, but rather a ‘top-down’ estimate of EI applied to all water agencies located within each zone. For reference, LADWP is located within the South Coast hydrologic zone. This statewide study also includes the long-range conveyance systems delivering to each hydrologic zone, but it does not reflect the specific contribution of this imported water to the water supply portfolio for each water agency within the zone (Navigant 2015b).

2.1.1. Scenario EI1

In their 2015 Urban Water Management Plan (UWMP), LADWP provided a complete assessment of the EI of their water supply infrastructure (LADWP 2016a). LADWP performed the EI analysis in accordance with voluntary draft guidelines established by the California Department of Water Resources (DWR) per Section §10631.2(a) of the California Water Code (CWC) (LADWP 2016a). The water and energy data provided in the UWMP covered 2010–2015 and was disaggregated by water source and infrastructure process.

Scenario EI1 focuses on the energy consumed by water infrastructure assets operated directly by LADWP within their service territory, and thus, the EI of imported water is not included in this scenario. Water treatment, groundwater pumping, and distribution pumping represent the core energy consuming processes within this system boundary. While LADWP does recycle water, this portion of their system was excluded from the analysis, since it is not directly reused within the potable water system, and further, not specifically targeted by LADWP in its water conservation programs. To estimate the total EI across the processes (groundwater pumping, all water treatment plants (n), and distribution) included in EI1, we calculated average annual values (based on data range from 2010 to 2015) and applied a flow-weighted average across all water pathways (equation (1)).

$$EI1_w = \frac{\left[\left(EI_{gw} + EI_{dist}\right)V_{gw}\right] + \sum_{i=1}^{n}\left[\left(EI_{t,i} + EI_{dist}\right)V_{t,i}\right]}{V_{gw} + \sum_{i=1}^{n} V_{t,i}} \tag{1}$$

where:

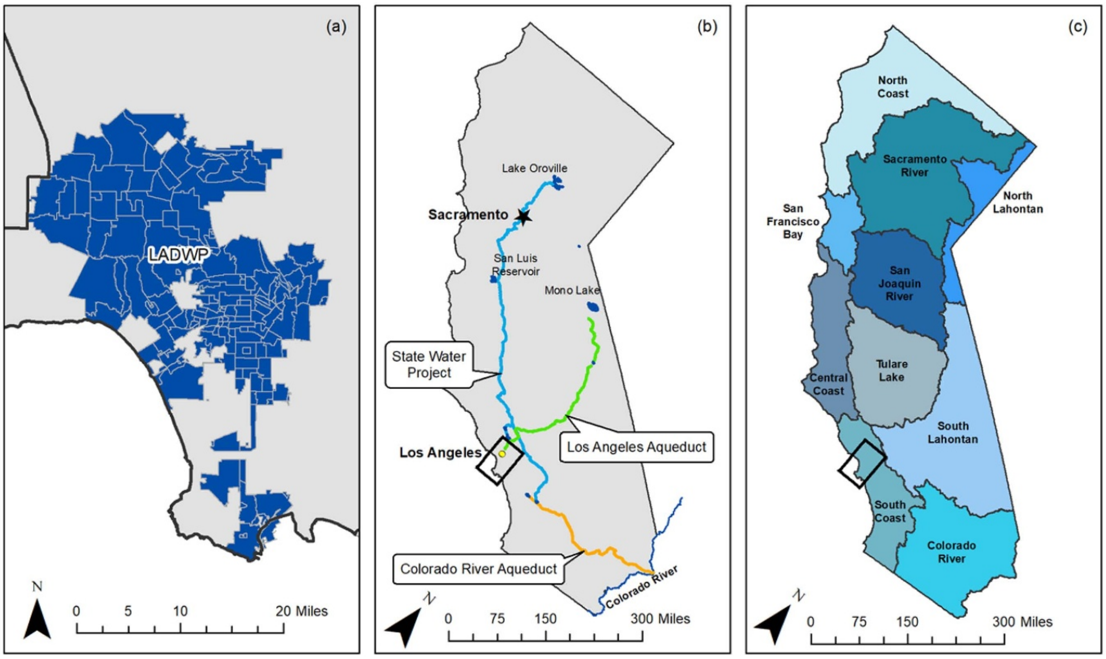

Figure 1. System boundaries for three EI scenarios: (a) LADWP water service territory (EI1); (b) LADWP water service territory with the SWP, LAA, and CRA imported water conveyance systems included (EI2); and (c), the 10 hydrologic zones of California, including South Coast where LADWP is located (EI3).

$EI1_w$ = overall potable water EI value for EI1 scenario

EI_{gw} = EI of groundwater pumping

EI_{dist} = EI of distribution pumping

V_{gw} = Volume of groundwater supplied

$EI_{t,i}$ = EI of water treatment for each treatment plant, i

$V_{t,i}$ = Volume of treated surface water supplied from each treatment plant, i.

To estimate the EI of the wastewater system, we collected data directly from LASAN that included total annual energy use by all wastewater lift stations, energy use by all wastewater treatment plants, and total volume of wastewater collected and treated (equation (2)). We estimated an annual average value based on the range of data collected from LASAN, 2008–2013.

$$EI1_{ww} = \frac{(E_{ls}+E_{wwt})}{V_{ww}} \qquad (2)$$

where:

EI_{1ww} = overall wastewater EI value for EI1 scenario

E_{ls} = total energy use by wastewater lift stations

E_{wwt} = total energy use by wastewater treatment plants

V_{ww} = total volume of wastewater collected and treated.

2.1.2. Scenario EI2

The potable water EI estimate for the second scenario (EI2) also derives from LADWP's 2015 UWMP (LADWP 2016a). For this estimate, the potable water EI system boundary was extended to include the long-range water conveyance (SWP, LAA, and CRA) and treatment systems for their imported water. Figure 2 provides an additional visualization of this extended system boundary for EI2 relative to EI1, as well as a representation of the main volumetric flows from water source through use to discharge. Note that the Jensen, Weymouth, and Diemer water treatment plants are not included in the EI1 system boundary, since they are owned and operated by LADWP's upstream imported water provider, the Metropolitan Water District (MWD).

EI2 was calculated by adding the flow-weighted averages of EI for all the conveyance systems (n) to the LADWP service territory EI value (EI1) calculated in the preceding section (equation (3)). As mentioned previously, the LAA system is a net energy producer; however, for the purpose of this study, we assume the EI of the LAA system to be zero. This approach aligns directly with how LADWP calculates systemwide EI. As stated in the UWMP, the 'energy intensity of the LAA is not included in LADWP's total water system energy intensity, since the energy generated does not directly offset the energy required for other sources of water' (LADWP 2016a, p 355).

$$EI2_w = \frac{\sum_{j=1}^{n}(EI_{c,j})V_{w,j}}{\sum_{j=1}^{n}V_{w,j}+V_{gw}} + EI1_w \qquad (3)$$

where:

$EI2_w$ = overall potable water EI value for EI 2 scenario

$EI_{c,j}$ = EI of for each conveyance aqueduct, j

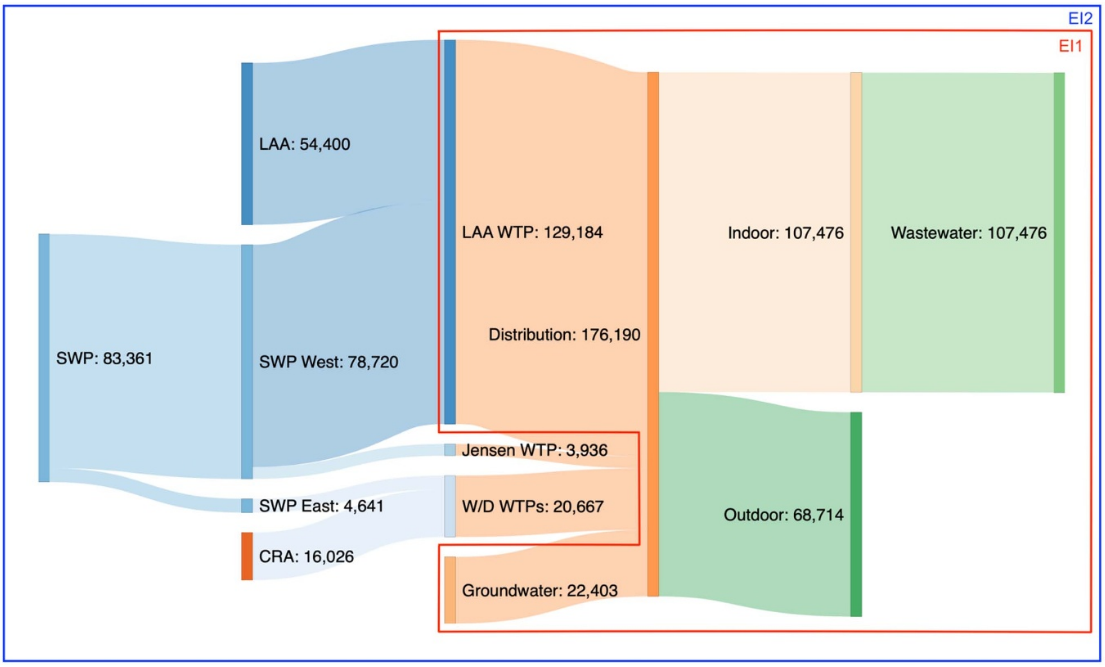

Figure 2. System Boundaries for Scenarios EI1 and EI2 with corresponding LADWP water system flows (MG) from source to discharge. SWP = State Water Project; LAA = Los Angeles Aqueduct; CRA = Colorado River Aqueduct; WTP = Water Treatment Plant; W/D WTPS = Weymouth and Diemer Water Treatment Plants. Red and blue outlines delineate the system boundaries for scenarios EI1 and EI2, respectively. Figure derived directly from LADWP data (LADWP 2016a).

$V_{w,j}$ = Volume of water for each conveyance aqueduct, j.

The wastewater EI value for EI2 ($EI2_{ww}$) is the same as for EI1 ($EI1_{ww}$) since the system boundary for wastewater collection and treatment remains unchanged.

2.1.3. Scenario EI3

The EI values for both water and wastewater in scenario 3 (EI3) were obtained directly from a CPUC report that contains statewide estimates of EI on a hydrologic zone basis (Navigant 2015a). We used the estimates for the South Coast hydrologic zone where LADWP is located.

2.1.4. EI for indoor and outdoor water use

For all scenarios, when considering the integration of water and wastewater EI values, it is important to distinguish between ‘outdoor’ and ‘indoor’ water use. Outdoor water use generally refers to end uses where the water is not ultimately treated as wastewater after use. For example, water used by outdoor sprinklers for turf irrigation is treated and delivered as potable water to the user, but the water returns directly to the environment rather than being collected and treated within the wastewater system. Thus, in the case of EI for outdoor water use (EI_o), the EI_o is simply equivalent to the upstream EI of the potable water system (i.e. $EI_o = EI_w$). In contrast, indoor water use represents all household uses where the water is directed into the wastewater system after use, i.e. sinks, showers/baths, and toilets. Thus, the EI of indoor water use (EI_i) includes the EI of the upstream potable water system (EI_w) as well as the EI of the downstream wastewater system (EI_{ww}). Thus, $EI_i = EI_w + EI_{ww}$. As a reference, LADWP estimated that 61% of their total water use is for indoor use and 39% is for outdoor use in their UWMP (LADWP 2016a), which is also reflected in the volumetric flows shown in figure 2.

2.2. LADWP water and energy program savings

The following sections summarize the process for collecting and consolidating data on the costs and estimated savings of LADWP’s water conservation and EE programs.

2.2.1. Water conservation programs

LADWP has a strong record of achieving water savings through hardware-based (e.g. installing more efficient showerheads) and behavioral interventions (e.g. encouraging customers to reduce the frequency or duration of outdoor irrigation). For our comparison, we consolidated data for nine hardware-based water conservation measures from LADWP’s 2015 UWMP (LADWP 2016a). This 5 years report provides aggregated data for measures implemented for residential and commercial users from FY 2010/11 through 2014/15. These data include the name of the measure, units installed, rebate costs, and estimated water savings per year. Given the five-year aggregation of program data for water conservation measures in the report, we derived annual estimates by dividing the total units installed as well as the total estimated water savings by five.

The estimated annual cost of water conservation interventions was then calculated as the summation of the annual direct costs for the utility incentives and the overhead cost for each program. We applied a 9% overhead cost factor based on a direct audit of LADWP water conservation programs (Galperin 2015). Table 1 provides a summary of the estimated annual water savings and utility costs for FY 2010/11 through 2014/15 by program type (commercial/residential, indoor/outdoor, and specific hardware installation), as well as the estimated lifespans for the installed hardware based on a previous study by Gleick *et al* (2003).

2.2.2. Energy efficiency (EE) programs

Program descriptions and performance results for LADWP's EE programs were primarily obtained from annual reports that are required of public energy providers under State Senate Bill 1037 (SB1037) (California Municipal Utilities Association 2014). These data include gross annual savings, units installed, incentive amounts, and lifetime of individual measures. For instances of incomplete program data, additional data were extracted directly from the underlying EE program reporting tool that LADWP has used to inform its annual SB1037 reports since 2010 (LADWP 2017).

Whereas LADWP presents their water conservation program evaluation data over a five-year period, the EE program data is presented on an annual basis. Further, their EE program portfolio had substantial variation from year to year, complicating efforts to take five-year average data similar to the water programs. Instead, we selected an individual year, FY 2012/13, as the midpoint reference year to compare with our annualized water conservation program data. For the 2012/13 reference year, 13 EE programs had sufficient data to complete the cost-effectiveness analysis. Overhead costs are reported as the cost of administering EE programs (e.g. staff salaries, administration, marketing, as well as program evaluation, monitoring and verification (EM&V)). All these data are presented in table 2, along with the expected lifespan for each EE program, taken from Hoffman *et al* (2015).

2.3. Levelized cost of saved energy (LCSE)

Using the EI scenarios described above (EI1, EI2, EI3), we converted all of the water savings achieved through the water conservation programs (table 1) to energy savings. For water conservation programs targeting outdoor water use (e.g. sprinklers), we converted water savings to energy using the outdoor water EI (EI_o) estimate for that scenario. For indoor water use programs (e.g. toilets) we applied the indoor water EI (EI_i), which includes both water and wastewater EI (equations (4) and (5)).

For outdoor water conservation measures:

$$ES_o = WS_o \times EI_o \tag{4}$$

where,

ES_o = electricity savings estimated from reduction of outdoor water use (kWh).

WS_o = outdoor water savings reported by LADWP (MG).

EI_o = Energy intensity estimate (kWh/MG) for outdoor water use.

For indoor water conservation measures:

$$ES_i = WS_i \times EI_i \tag{5}$$

where,

ES_i = electricity savings estimated from reduction of indoor water use (kWh).

WS_i = indoor water savings reported by LADWP (MG).

EI_i = Energy intensity estimate (kWh/MG) for indoor water use.

While estimating total energy savings for each water conservation program is a necessary first step, it is not sufficient for directly comparing the performance of various interventions. The savings achieved by all interventions need to be normalized by program cost, while also taking into account the expected duration, or lifespan, of program savings. To achieve this, we calculated the LCSE for all programs (both water conservation and EE programs) to enable direct comparison.

The LCSE is a concept developed in the energy sector to account for 'the cost of acquiring energy savings that accrue over the economic lifetime of the actions taken through a program/sector/portfolio, amortized over that lifetime and discounted back to the year in which the costs are paid and the actions are taken' (Billingsley *et al* 2014, p13). The inclusion of a discount rate into the lifetime cost of energy savings raises the cost of conserved energy by discounting future benefits, and it also provides a basis for comparing cost of conserved energy for measures that have different lifespans (Meier 1982).

This metric is currently used by utilities to characterize and report the costs of energy savings achieved by the programs in their EE portfolios. Following these criteria, the LCSE was calculated for each of LADWP's EE and water conservation programs included in the study using equations (6) and (7) (adapted from Billingsley *et al* 2014)

$$LCSE = (C_e \times CRF)/ES \tag{6}$$

$$CRF = [d \times (1+d)^y]/[(1+d)^y - 1] \tag{7}$$

where,

$LCSE$ = Levelized cost of saved electricity in $\$\,\mathrm{kWh}^{-1}$.

Table 1. Summary of average annual water savings and expenditures for LADWP water conservation efforts (FY 2010/11 to 2014/15).

Water Conservation Program			Rebate Cost per Unit (US$)	Units Installed (#)	Unit Lifespan (Years)	Annual Water Savings (MG)	Cost of Rebates (US$)	Overhead Cost (US$)	Total Utility Cost (US$)
Residential	Indoor	HE Toilets	100	12 847	20	567	1 284 680	115 621	1 400 301
		HE Washers	300	7913	12	434	2 374 020	213 662	2 587 682
	Outdoor	Irrigation—RNSH	6	4291	10	31	25 747	2317	28 064
		Irrigation—WBIC	200	184	20	14	36 720	3305	40 025
Commercial	Indoor	HE Toilets	150	56 246	20	2255	8 436 930	759 324	9 196 254
		PHE Toilets	200	2423	20	145	484 680	43 621	528 301
		HE Urinals	500	876	20	174	437 900	39 411	477 311
	Outdoor	Irrigation—RNSH	6	5232	10	38	31 393	2825	34 219
		Irrigation—WBIC	50	2867	20	62	143 340	12 901	156 241

Notes: ‘HE Toilets’ = High-efficiency toilets; ‘HE Washers’ = High-efficiency clothes washing machines; ‘Irrigation—RNSH’ = Rotating nozzle sprinkler heads; ‘Irrigation—WBIC’ = Weather-based irrigation controllers; ‘PHE Toilets’ = Premium high-efficiency toilets; ‘HE Urinals’ = Zero and ultra-low flow urinals.

Table 2. Summary of annual savings and expenditures for LADWP EE efforts for FY 2012/13.

Energy Efficiency Program		Units Installed (#)	Unit Lifespan (Years)	Annual Energy Savings (kWh)	Direct Costs (US$)	Overhead Costs (US$)	Total Utility Cost (US$)
Residential	Home—HEIP	7716	19	623 933	942 619	6 082 981	7 025 600
	Refrigeration—LIREP	8727	14	6 850 881	4 411 618	490 637	4 902 255
	Refrigeration—RETIRE	2508	5	4 880 568	196 928	—	196 928
	Rebate—CRP	16 123	16	1 640 141	1 174 305	—	1 174 305
Commercial	Small Business—SBDI	49 522	11	1 832 296	206 809	—	206 809
	School—LAUSD	1	11	2 884 437	3 097 500	—	3 097 500
	Lighting—CLEO	178 335	12	36 031 248	5 475 574	5 572 518	11 048 092
	Building—RCx	44 110	5	53 814	3515	177 769	181 283
	Chiller—CEP	17 528	20	4 705 777	1 996 646	2 142 740	4 139 386
	Refrigeration—RP	20 613	4	1 465 731	48 036	221 661	269 697
	Custom—CPP	64 482 687	20	64 482 687	6 917 583	6 994 154	13 911 737
	Building—SBD	248 657	15	1 740 601	224 995	396 120	621 115

Notes: ‘Home—HEIP’ = Home Energy Improvement Program; ‘Refrigeration—LIREP’ = Low-Income Refrigerator Exchange Program; ‘Refrigeration—RETIRE’ = Refrigerator Turn-in and Recycle; ‘Rebate—CRP’ = Consumer Rebate Program; ‘Small Business—SBDI’ = Small Business Direct Install; ‘School—LAUSD’ = Los Angeles Unified School District; ‘Lighting—CLEO’ = Commercial Lighting Efficiency Offering; ‘Building—RCx’—Retrocommissioning Express; ‘Chiller—CEP’ = Chiller Efficiency Program; ‘Refrigeration—RP’ = Refrigeration Program; ‘Custom—CPP’ = Custom Performance Program; ‘Building—SBD’—Savings by Design.

Table 3. Three scenarios of EI estimation for LADWP water and wastewater services (and outdoor and indoor water use).

	Energy Intensity (kWh/MG)		
Scenarios	Water EI, EI_w (Outdoor)	Wastewater EI, EI_{ww}	Total EI (Indoor)
EI1	837	1651	2488
EI2	5210	1651	6861
EI3	5947	1283	7230

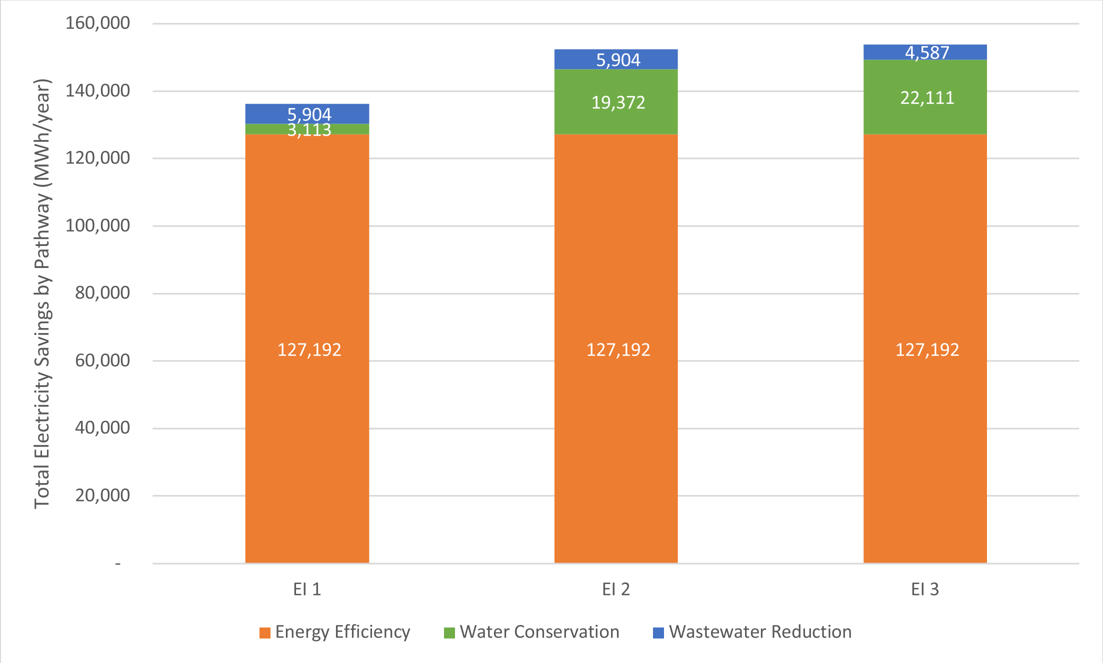

Figure 3. Total energy savings (MWh) achieved by savings pathway. Pathways include EE programs for FY 2012/13 and annual average for water conservation programs for FY 2010/11 through FY 2014/15, including both water and wastewater system energy savings.

C_e = Cost of the electricity savings program (or water conservation program) in US$

CRF = Capital Recovery Factor

ES = Energy savings achieved through the implemented program, in kWh

d = Discount rate; assumed 4.5% (Billingsley *et al* 2014).

y = Estimated program lifetime in years.

3. Results and discussion

The following section presents the results of our estimations for the LADWP indoor and outdoor EI values across system boundary scenarios (EI1, EI2, and EI3), the electricity savings achieved through LADWP's water conservation program portfolio, and the costs of saving electricity through water conservation as compared to direct EE programs.

3.1. EI estimates

Table 3 summarizes the indoor and outdoor EI values for scenarios EI1, EI2, and EI3. The expansion of the system boundary from the local service area (EI1) to include all the imported water sources (EI2 and EI3) significantly increases the potable (outdoor) water EI. The results show a roughly a 6-fold increase between $EI1_w$ (837 kWh MG^{-1}) and $EI2_w$ (5210 kWh MG^{-1}) and a 7-fold increase between $EI1_w$ and $EI3_w$ (5947 kWh MG^{-1}). Despite similar system boundaries for $EI2_w$ and $EI3_w$, the hydrologic zone-based estimate ($EI3_w$) is ~14% higher than LADWP's own imported water estimate ($EI2_w$). See tables SI-1, SI-2, SI-3, and SI-4 (available online at https://stacks.iop.org/ERL/15/114031/mmedia) for detailed LADWP flow and EI data used to estimate EI_w values for Scenario EI1 and EI2.

Wastewater EI estimates $EI1_{ww}$ and $EI2_{ww}$ are equal by definition (1651 kWh MG^{-1}), while the hydrologic zone-based estimate ($EI3_{ww}$) is ~22% lower (1283 kWh MG^{-1}). See tables SI-5 and SI-6 for detailed annual estimates of wastewater EI for LASAN, 2009–2014.

The estimates for total EI, or indoor EI (EI_i), also show high variance between estimates, but the variance is somewhat modulated by the more consistent wastewater EI estimates. Both $EI2_i$ (6861 kWh MG^{-1}) and $EI3_i$ (7230 kWh MG^{-1}) are roughly 3-fold higher

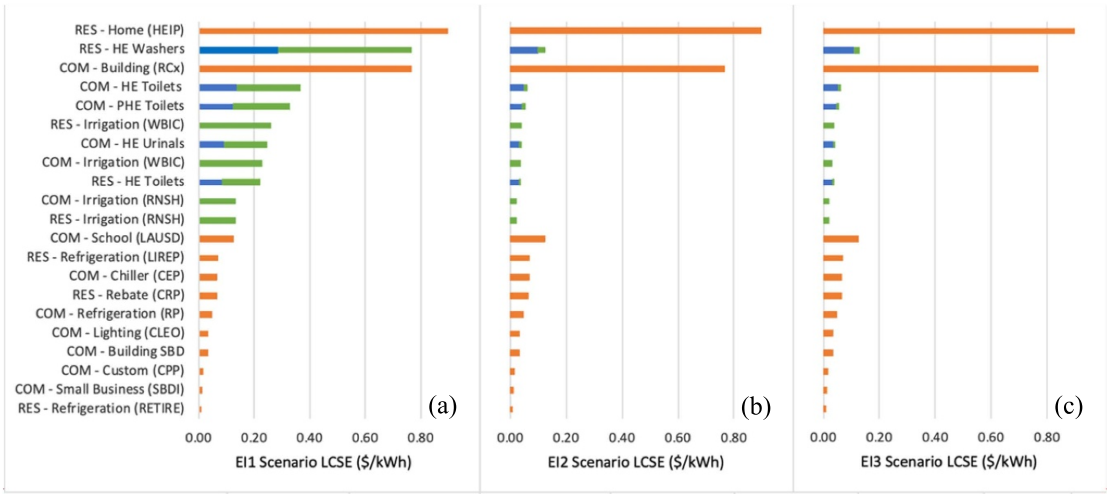

Figure 4. Estimated LCSE for LADWP EE (orange) and water conservation programs using EI scenario estimates (EI1, EI2, EI3). The green portion of water conservation-based LCSE represents water system energy savings and the blue portion represents wastewater system energy savings. Thus, green = outdoor water LCSE and green + blue = indoor water LCSE.

than $EI1_i$ (2488 kWh MG^{-1}); and, $EI3_i$ is 5% higher than $EI2_i$.

In sum, the wide variation in the EI values across scenarios highlight the importance of clearly identifying the water utility system boundaries for estimating EI. One system boundary is not necessarily better than another, the selection depends on the how the EI estimate will be used. In the case presented, EI1 would be an appropriate system boundary if LADWP was trying to calculate how much electricity savings could be achieved within its core service territory. However, if they were seeking an estimate of total statewide electricity savings, EI2 or EI3 would be a better approach. Meanwhile, EI2 and EI3 differ mainly in the specificity of the estimate. EI2 is likely to be the more precise estimate as it is based directly on the actual EI values for the portfolio of water pathways for LADWP, while EI3 is a larger estimate that assumes that all water utilities within the South Coast hydrologic zone have a similar blend of source waters with estimated EIs. Given the broad discrepancy in specificity, the regional estimate (EI3) is a surprisingly decent predictor of EI for LADWP. However, it may not be specific enough (i.e. ±5% for EI3 estimates relative to EI2) to engender sufficient confidence to support investments in the water sector to secure targeted electricity savings.

3.2. Energy savings from water conservation

Meanwhile, average annual water savings for FY 2010/11 through 2014/15 for LADWP's water conservation programs considered in this study was approximately 3720 MG; and. When these water savings were converted to energy savings using the three EI scenario estimates, the total energy savings from these programs were 9017 MWh (EI1), 25 276 MWh (EI2), and 26 698 MWh (EI3). These values represent roughly 7.1%, 19.9%, and 21.0% of the total energy savings achieved from targeted EE programs enacted over a similar time period (FY 2012/13). The relative electricity savings by savings pathway (i.e. EE programs or water conservation efforts, including both electricity savings from water and wastewater infrastructure savings) are summarized in figure 3.

Figure 3 also demonstrates the influence of EI geographic scale (EI scenarios 1–3) on estimated electricity savings. While the wastewater system energy savings does not change much between scenarios, the water system energy savings reflects the 7-fold difference between the EI1 and EI3 estimates.

3.3. LCSE of EE and water conservation programs

In addition to estimating total electricity savings achieved by program, it is also important to understand the relative cost-effectiveness of the programs using the LCSE metric. Figure 4 summarizes the results of comparing the LCSE of LADWP's EE programs to the LCSE of their water conservation program using the three EI estimates. For detailed data on LCSE for all programs and scenarios, see table SI-7.

For scenario EI1 (figure 4(a)), the LCSE values for water conservation programs range between \$0.14 kWh^{-1} for the Rotating Nozzle Sprinkler Head (RNSH) residential and commercial programs and \$0.78 kWh^{-1} for the residential High-Efficiency Washing Machine (HE Washers) program, while the LCSE achieved through EE programs ranges from \$0.01 kWh^{-1} for the Refrigerator Turn-in and Recycle (RETIRE) residential program and the Small Business Direct Install (SMDI) commercial program to \$0.90 kWh^{-1} for the Home Energy Improvement Program (HEIP) residential program. As a reference value, the average price of electricity over the period 2010–2015 in the Los Angeles region was ~\$0.21 kWh^{-1} (U.S. Bureau of Labor Statistics 2020)

It is worth noting that the two most cost-effective water conservation programs (and four of the top six programs overall), only target outdoor water savings. Thus, even though these programs do not benefit from additional energy savings from avoided wastewater collection and treatment, they are able to produce highly competitive energy savings on the upstream side of the water meter (extraction, conveyance, treatment, and distribution).

As expected, the LCSE of the water conservation programs decrease dramatically when using the higher EI estimates defined by scenarios EI2 and E13. Thus, both of these scenarios suggest even greater cost-competitiveness of water conservation-based LCSE with EE program LCSE (figures 4(b) and (c)), as compared to EI1 (figure 4(a)). Under scenarios EI2 and EI3, LCSE values for water conservation programs range from \$0.02 kWh^{-1} to \$0.13 kWh^{-1}, and eight of the nine water conservation programs are more cost-effective for saving energy than six of the 12 EE programs. Across all scenarios, securing energy savings through water conservation proves to be cost competitive with at least two of the EE programs—the residential home energy improvement program (HEIP) and the commercial building retro-commissioning (RCx) program. Thus, the results suggest that saving energy through water conservation programs (except for the residential high-efficiency washing machine program) is highly cost-competitive with direct EE programs in the LADWP service area.

4. Conclusions

This study estimated the energy savings associated with water conservation programs in the LADWP service area using three different EI estimates of outdoor and indoor water use. We used direct estimates of EI for LADWP and LASAN for the service territory (EI1) and service territory with extended conveyance system (EI2), as well as a broader regional estimate for LADWP and LASAN's South Coast hydrologic zone (EI3). This comparison across EI scenarios is highly relevant to both water and energy utilities, as well as government agencies with mandates to sustainably manage water supplies, achieve energy efficiency savings, and reduce GHG emissions. This metric is essential for calculating the energy and GHG reduction benefits achieved per dollar invested in water conservation programs.

The study results provided two key insights: that the system boundary for determining water system EI can have a significant influence on the cost-effectiveness of water-based energy savings, and that water conservation programs can be cost-competitive (and in some cases, more cost-effective) at generating energy savings than EE programs.

This case study of LADWP demonstrates that the geography and topography of water utilities matter, and that consistent data and reporting is needed for both effective policy and meaningful comparison. The higher EI values utilized in scenarios EI2 and EI3 are mostly a result of expanding the LADWP water-energy system boundary to include the larger water extraction and conveyance infrastructure that delivers water from northern California and the Colorado River to the South Coast hydrologic region. Taking this broader perspective allows for the tabulation of increased energy benefits per unit of water saved in the LADWP territory. Thus, while LADWP may not receive all the energy savings benefits of their investments in water conservation, additional energy savings (and associated GHG emissions reductions) do manifest at the statewide level. These results could then inform the design of multi-party incentive programs to offset LADWP's investments in water conservation, thereby rewarding them for the extraterritorial energy and GHG benefits that would not otherwise accrue to them as the implementing utility. While the study does address the variability of EI values over a range of system boundaries, we did not have sufficient data to track temporal variation of LADWP's EI to capture the potential influence of seasonality, changing hydrologic conditions, and other external factors. We suggest future studies incorporate this additional dimension.

We then compared the cost effectiveness of securing energy savings through water conservation to the costs of energy savings secured through directly administered EE programs. To normalize this comparison, we estimated the LCSE for all programs. LCSE proved to be a reliable metric for comparing energy savings achieved by both the water and energy sectors and should be utilized for the future evaluation of projects that specifically target securing energy savings through water conservation.

Across all EI scenarios, the results showed that water conservation programs were largely cost-competitive with direct EE programs. These results corroborate previous results of a cost-effectiveness study of statewide energy savings achieved through urban water conservation during the recent California drought (Spang *et al* 2018). Thus, these two studies have converged on this same result using analyses at two very different scales—statewide and utility-specific. For this utility-specific study, not only were the EI estimates downscaled for the LADWP water system (EI scenarios 1 and 2), but we also assessed water conservation and EE programs that were implemented directly by LADWP within their service territory.

At the utility level, it appears that there are opportunities to take greater advantage of energy savings through increased water conservation as well. In the 2018/2019 fiscal year budget, LADWP allocated more than five times more money to EE programs (∼\$147.1 M) than to water conservation programs (∼\$27.7 M) (LADWP 2016bb). Meanwhile, the Mayor of Los Angeles has set aggressive targets to reduce per capita water use by 30% by 2035 (relative to 2014 baseline) (City of Los Angeles 2015). Perhaps an increased allocation of EE dollars to water conservation would provide the resources necessary to secure these target water savings while also providing sufficient EE returns required for investment of these funds. This conclusion is also pertinent at the state level, where roughly $3 billion dollars per year are available for energy efficiency investments and GHG reduction (Kenney *et al* 2019, California Climate Investments 2020), but only ∼$10 M in state funding is available for water conservation (California Department of Water Resources 2020). Rarely do such 'win-win' (or even 'win-win-win') opportunities exist in resource management, and we believe that ample opportunity exists to take greater advantage of these leveraged savings in California and beyond.

Acknowledgments

The Authors would like to thank LADWP for funding this research, and both LADWP and LASAN for generously sharing their data and knowledge to enable this analysis. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the funding agency. We also would like to thank Lauren Mabe for assistance with digital mapping expertise to produce figure 1 in the manuscript.

Data availability statement

All data that support the findings of this study are included within the article (and any supplementary information files).

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