Paper ID APEN-MIT-2020_307
Applied Energy Symposium: MIT A+B
August 12-14, 2020 • Cambridge, USA

Demand Response in Water Supply and Wastewater Systems: What are the Opportunities?

Angineh Zohrabian
Dept. Civil and Environmental Engineering
University of Southern California
Los Angeles, CA
azohrabi@usc.edu

Kelly T. Sanders
Dept. Civil and Environmental Engineering
University of Southern California
Los Angeles, CA
ktsanders@usc.edu

Abstract—Growing interest in greenhouse gas mitigation strategies to address global climate change has resulted in the rapid expansion of renewable electricity sources. Increasing energy generation from variable renewable electricity sources, such as solar photovoltaics and wind turbines, has made balancing electricity supply and demand across the power grid more challenging. Some grid management challenges include sharp ramp up needs when the sun goes down, and the overgeneration of renewables when demand is low. In absence of cost-effective, utility-scale batteries, demand response strategies that leverage flexibility in electricity consumption have gained interest as readily available resources to address the temporal mismatch between renewable energy availability and high energy demand periods. The water industry (i.e., water supply and wastewater systems) includes industrial customers that are particularly attractive in terms of demand response potential as they can offer flexibility through large water storage capacities, large interruptible pumping loads, and energy generation opportunities. This study highlights an illustrative case in California to demonstrate the emissions benefits of load shifting in the water industry, followed by discussions regarding potential flexibility opportunities based on the recent literature and directions for future research opportunities to support the implementation of flexibility measures.

Keywords—demand response, load flexibility, urban water systems, renewable curtailment, greenhouse gas emissions

I. INTRODUCTION

The growth of variable renewable energy sources, namely solar and wind energy, is markedly changing the dynamics of the electric grid. Large penetrations of solar photovoltaic (PV) and wind generators have created grid conditions in which generator fleets are composed largely of renewable energy in some hours, and of non-renewable generators (mostly fossil fuel-based) in other hours of the day when wind and solar resources are diminished (See Fig. 1). High fractions of solar energy can create large gaps between net load in the middle of the day versus net load in the evening hours, when solar generators go offline. (Net load refers to the difference between forecasted load and expected electricity production from variable generation resources, i.e. solar and wind energy, a phenomenon known as “Duck Curve” [1].) The Duck Curve highlights two major challenges, the risk for “overgeneration” and the large ramp up requirements of dispatchable generators that come online in the evening as solar generation diminishes. The risk for overgeneration occurs when expected electricity generation (including renewables) exceeds real-time demand, and as a result, renewable energy generation is curtailed, wasting a zero emissions source of generation. Renewable electricity curtailments have grown, particularly in grids where there are large fractions of solar generation and an absence of utility-scale storage (e.g., the California Independent System Operator, CAISO) [2]. Likewise, the challenge of large ramping requirements in the evening hours when demand is large and solar generators become unavailable has been exacerbated by growing solar PV penetration in California when the loss of solar generation is coincident with daily peak electricity demand times.

Flexible resources are needed to support balancing supply and demand across the grid. Flexibility can come from various supply-side solutions such as battery storage, flexible power generators, and long-distance transmission [3]. Demand-side resources can also add flexibility by modifying electricity consumption patterns to better match grid conditions [4], by shifting non-essential electric loads from hours when renewable energy generation is low (typically when wholesale market prices are high) to hours when there is a surplus of renewable generation. Strategies to control demand have been employed in limited circumstances to curtail electric load during peak demand hours when the reliability of the electric grid is jeopardized (i.e., demand response events). More frequent demand response events could be valuable for easing the challenges of renewable integration into the electric grid. Furthermore, demand-side flexibility can be an environmental tool to support mitigating greenhouse gas emissions as the timing of electricity demand matters when it comes to emissions footprint of each unit of energy consumed. Since the fleet of generators producing electricity for the grid change throughout the day as a function of dynamic demand, renewable resource availability, and market dynamics, the grid’s real-time emissions intensity (defined as kg emitted CO_2 per unit of electricity consumed) fluctuates considerably throughout the day. In California, the grid generally has lower emissions intensities in the middle of day and very high intensities in the nighttime, as solar resources go offline (see Fig. 2). Thus, reducing electricity consumption during

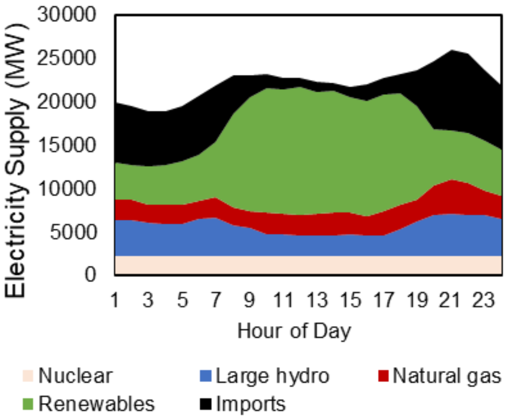

Fig. 1. Electricity supply portfolio in CAISO on May 20, 2019. Large hydro is included as a separate category from small hydro generation, which is considered renewable energy. Note that imported electricity has a different fuel mix, but it is difficult to specify its fuel source. In case of CAISO, electricity imports are typically dirtier than average in-state generation in CAISO [5].

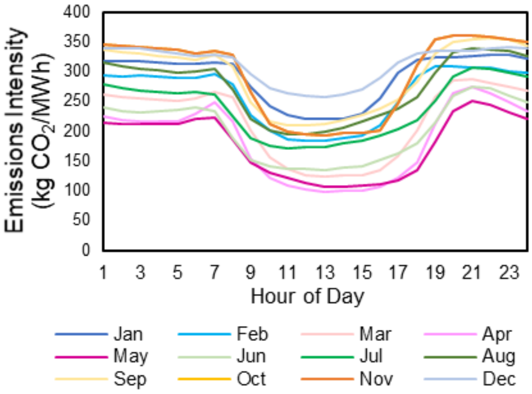

Fig. 2. Hourly emissions intensity of electricity consumed in the CAISO region based on a linear regression analysis of 2019 hourly emissions versus electricity demand data reported on CAISO Today's Outlook website [6].

certain hours has high emissions benefits, which should also guide demand-side energy management strategies. These diurnal trends are not unique to the case of CAISO, but they are more pronounced in electric grids with higher levels of renewable energy.

II. THE WATER INDUSTRY AS A FLEXIBILITY RESOURCE

In the industrial sector, water and wastewater systems are well-suited to offer load flexibility to the grid [7][8][9], thanks to advancements in control systems, digitalization, embedded water storage capacities and other features of the system. Municipal drinking water supply and wastewater management systems (collectively referred to as the "water industry" in this paper) represent a considerable share of the total energy use and greenhouse gas emissions of cities. Energy is consumed in the water industry for sourcing, conveying, treating and distributing water to consumers, as well as for managing wastewater for disposal or recycling [10][11]. One study reported that the water industry consumes roughly 1–18% of a city's electrical energy use [12]. In the US, about 2% of annual electricity consumption occurs in the water industry [13]. Given the major reliance of water services to energy, energy costs are typically significant operational costs in the water industry, often only behind labor cost [14]. Furthermore, peak electricity usage in water systems typically occurs in the morning and evening hours with higher peaks in summer months (reflecting water consumption behavior [15]); these periods often coincide with peak electricity consumption periods across the electric grid. Hence, energy management solutions, such as improving energy efficiency, recovering energy, and self-generating energy from distributed renewable sources, are of high interest in this industry.

Most studies that consider energy management solutions in the water industry focus on energy cost reductions that consider average cost of electricity, without incorporating the electric grid's real-time dynamics into their assessments [16][17]. The solutions identified traditionally result in emissions mitigation directly, by decreasing energy consumption (improving energy efficiency), or indirectly, by supplementing energy purchases from the electric grid with cleaner sources of energy. Facilitating flexible operation and prioritizing energy consumption at times when renewable energy is abundant (or at risk of curtailment) is a different and less common approach that can potentially increase greenhouse gas emissions mitigation. Such load management measures do not necessarily reduce overall energy consumption; instead they tend to shift the electric load to hours when the electricity generation fleet is cleaner. Electric utilities and third-party aggregators offer a range of programs to financially promote such load management measures [18]. Some DR research studies have attempted to incorporate electric grid dynamics in energy management strategies in the water sector and found economic value in providing flexibility services [19][20][21]. This paper illustrates a case study to highlight the water industry's diurnal emissions pattern and its resulting potential for emissions mitigation from load shifting measures. Then a summary of flexibility opportunities in the water industry is presented. The paper is concluded with challenges and future research directions that can support implementing flexibility measures in the water industry.

III. AN ILLUSTRATIVE CASE STUDY

Here we analyzed an illustrative case study to demonstrate how load shifting in the water sector can be beneficial from an emissions reduction perspective. We use hourly load data accompanied by California's Demand Response Potential Study [9] representing 97 electricity accounts within the water industry that include urban water supply and agricultural water pumping accounts with loads greater than 200 kW in year 2014, located within Pacific Gas and Electric utility balancing authority (the data is accessible at [22]). We calculated average hourly electricity load for each month. We assumed an electric load shifting scenario where 20% of daily average hourly demand is shiftable in one day for different durations between one to six hours. The amount of load increase in each hour is capped at the level of daily peak demand (see Fig. 3).

The load shifting scenario is considered to envision maximum environmental benefit; therefore, we assumed that during the cleanest hours of the grid (in this case, CAISO), the electric load can be shifted from the dirtiest hours to the cleanest. For example, in this analysis, a load shift of "3 hours" would mean that 20% of the water industry's daily average load, consumed during the CAISO's three "dirtiest hours" (i.e., hours with the highest penetration of

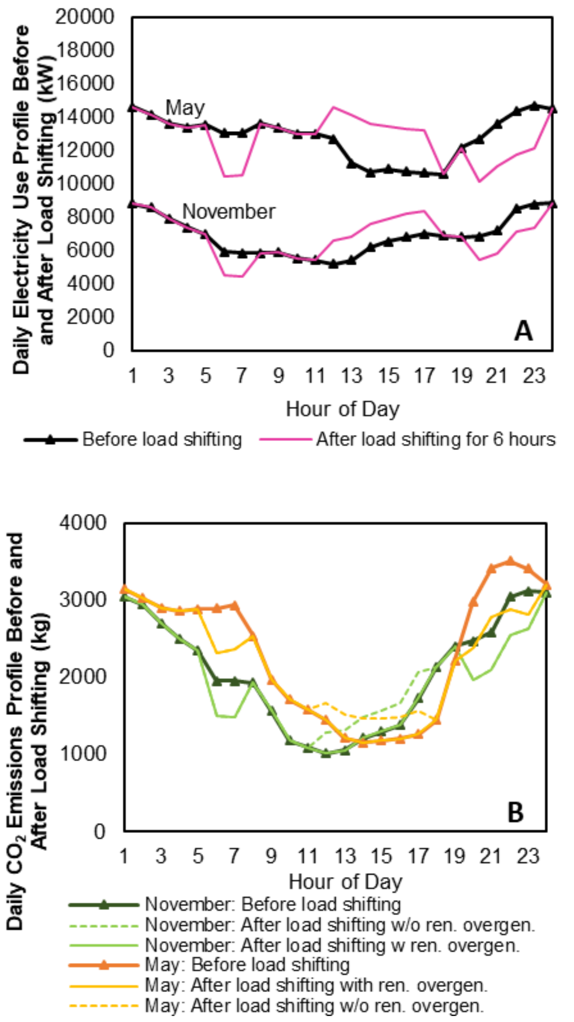

Fig. 3. Diurnal profiles for the aggregated electricity use (A) and CO_2 emissions (B) of the 97 electricity accounts analyzed within the water industry, before and after load shifting.

fossil fuels), would be shifted to the three “cleanest hours” (i.e., hours with the high penetration of clean electricity generation sources) of the same 24-hour period. In some cases, particularly for scenarios that have longer load shifts (e.g., 6 hours), the “dirtiest” and “cleanest” hours selected from the load shift might not consecutive (e.g., shifting load from the dirtiest hours between 6:00-7:00 and 20:00-23:00, to the cleanest hours between 12:00-17:00). We calculated total emissions based on CAISO’s average hourly emissions intensities, which are shown in Fig. 2. We first calculated emissions assuming no renewable energy curtailment occurs, and average hourly emissions intensities were applied to all hours of that month to estimate the hourly emissions footprint of electricity consumption before and after load shifting. Next, we calculated a second emissions estimate for the electric load after it was shifted to the middle of day, assuming that the curtailment of renewables occurs. We assume that accommodating this load during high-solar hours incurs zero additional emissions to simulate days with excess emissions-free solar energy. (Note that in CAISO, the average daily renewable curtailments due to overgeneration were over 670 and 370 MWh in May and November 2019 [23], respectively, which were much greater in magnitude than the amount of shiftable load explored in this case study). The results for 6-hour load shifting are summarized for May and November in Fig. 3. These two months are picked because the electric consumption patterns of water facilities are typically very different due to temporal differences in water consumption, and therefore, different in terms of the energy consumed for water services, the respective emissions intensities of the grid, and the risk for renewables overgeneration. Generally, we see that water-related energy use is greater in May, but one unit of electricity generated in November is much more greenhouse gas intensive than in May. Renewable energy curtailment is also greater in May than in November.

The total change in hourly emissions in one day is calculated as the sum of differences between the emissions associated with the aggregated electric load of the cluster of water utility accounts before and after load shifting (see Fig. 4). Additionally, an avoided emissions metric (*A*) (in kg CO_2 per kWh shifted load) is defined in Equation (1) where the sum of changes in emissions in each hour of the day (i) before and after load shifting (ΔE_i) is divided by total daily shifted load (which is hourly magnitude of load shifting (*S*) times duration of load shifting (*h*)) to inform the effectiveness of load shifting scenarios (see Fig. 5).

$$A = \sum_{i=1}^{24} (\Delta E_i \times (S \times h)^{-1}) \qquad (1)$$

A few trends are worth highlighting. Daily electricity consumption in November before load shifting had a flatter profile than in May, with significantly lower hourly loads (see Fig. 3). The amount of load shifted is assumed to be proportionate to the magnitude of electric load, so there is larger load shifting potential in May compared to November. Since more evening hours electricity consumption can be avoided in May than in November, the May shifting scenario results in more avoided emissions despite the emissions intensity of all hours being higher in November than May (see Fig. 2). Moreover, the amount of avoided emissions is much higher when excess generation from renewables is available meet the additional load shifted from evening hours to the midday. The duration of load shifting is also an important factor in affecting the total sum of emissions reduced in a day; the longer the duration for load shifting, the greater the amount of avoided emissions are (see Fig. 4). However, the emissions reduction metric shows that the emissions reduction potential of load shifting goes slightly down as the duration of load shifting increases (see Fig. 5). In other words, the emissions reduction potential of shifting load is the highest when the load is shifted from the dirtiest hour, in terms of the grid’s generation mix, to the cleanest hour of the day. In terms of seasonal trend, avoided emissions per unit of shifted load is higher in November as compared to May, although the absolute amount of reduced emissions is greater in May.

This analysis illustrates the potential aggregated emissions benefits of load shifting across a cluster of 97 water industry end users. Some of the underlying assumptions regarding ground facts are simplified or neglected and will impact results. For example, the constraints associated with providing water services and operating utilities may be prohibitive in terms of flexible operation as simulated. Other factors such as the electricity rates and utility programs may not be well aligned with the environmental preferences, and therefore, an optimum flexible operation in practice might be more price responsive. (However, in CAISO, low wholesale electricity prices are typically aligned with times of high renewable energy generation and inversely related to peak hours in the evening, supporting our assumptions regarding temporal shifts [24].) These factors can be utility-specific and should be integrated into load shifting strategy design to guide more holistic decision making that balances both economic and environmental benefits.

IV. FLEXIBILITY OPPORTUNITIES IN THE WATER INDUSTRY

This section describes several strategies and opportunities that support load flexibility in the water sector.

A *Leveraging water storage capacity:* Water storage tanks embedded in water systems can operate as energy storage capacity, since the ability to store water in storage tanks enables flexibility in the operation of pumps. Pumping water to fill a reservoir at times when renewable energy is abundant can support the curtailment of pumping load during hours when the electric grid is less clean (i.e., has a high emissions intensity) and electricity prices are more expensive. Sufficient storage capacities can support longer interruptions of pumping with less adverse effects on the system [25]. Advanced process monitoring and control systems in water facilities can be programmed to satisfy operational constraints and facilitate faster response to grid needs. For example, variable-speed-drive pumps can adjust their motor speed and water flow rates continuously, and therefore, they support flexible operation when water storage capacities and grid conditions are aligned to support baseload and peak load management, as well as water system requirements [26].

B *Controlling operational load:* Water treatment facilities are typically equipped with central control systems to manage treatment processes and water quality. These control systems can help maintain treatment and pumping processes to operate closer to the facility's full operational capacity during hours when electricity is cleaner. Control systems can also schedule delays in treatment or switch to low operational modes at times when electricity is dirtier [27]. This type of load management may utilize flow equalizers and storage tank capacity, in addition to the individual components of a treatment process. Aeration units are often the largest energy consumers in wastewater treatment facilities with secondary treatment. They can be operated intermittently to control the load. However, advanced energy and water quality management systems are necessary for the water industry to determine an optimal daily plan for operating water systems, while ensuring that load management will not compromise water utilities' services [28]. Some components of a wastewater treatment plant can be turned off for a few minutes up to a few hours [29]. Pumping systems can typically be interrupted for longer periods than treatment systems depending on the system characteristics and water delivery constraints [30]. Some water utilities already manage their electricity use to limit consumption during expensive time-of-use rates (that typically reflect higher wholesale electricity generation costs). For instance, Irvine Ranch Water District reduced significant amounts of its electrical load between noon to 18:00 on summer weekdays, primarily (but not solely) through limiting the operation of its groundwater and drinking water pumps [31].

C *Utilizing on-site generation resources:* The primary goal of running on-site generation resources is to reduce electricity purchases. Engaging on-site generation resources in load shifting strategies at a water facility might not minimize its overall electricity purchases from the grid, but strategies that reduce overall load on the electric grid when electricity is generated from dirtier the resources can result in environmental and grid management benefits. Aside from large hydropower generation plants located within some large water transfer projects (whose

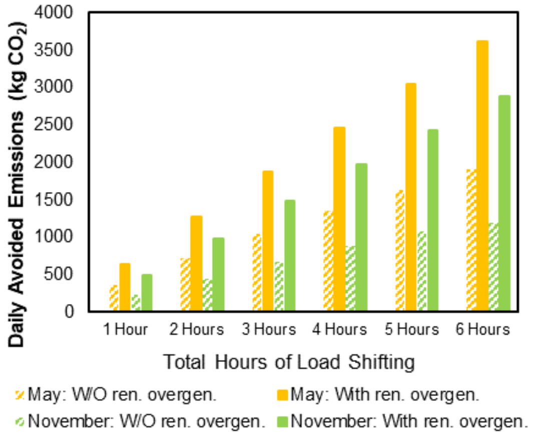

Fig. 4. Average daily avoided CO_2 emissions due to load shifting one to six hours for scenarios with and without renewable energy overgeneration.

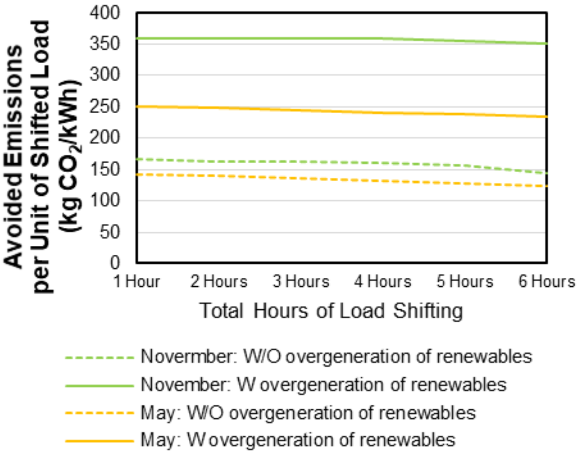

Fig. 5. Average daily avoided CO_2 emissions per unit of shifted load versus total duration of load shifting

generated electricity is often sold to the electric utility, and is thus, generally decoupled from urban water systems), there are several other energy generation opportunities. Some technologies can help recover small amounts of energy from pressurized water systems such as in-pipe hydro turbine and pump as turbine technologies [32][33]. These energy generation resources are attractive for improving flexibility capabilities when they are coupled with energy storage technologies.

Anaerobic digestion units can recover larger amounts of energy from organic materials in the form of biogas from wastewater. Biogas can be burned as a fuel in power generation units, such as internal combustion engines, micro-turbines, gas combustion turbines, and fuel cells [34][35]. Typically wastewater treatment facilities with influent flow rates of 5 million gallons per day or greater are more cost-effective to produce biogas in quantities adequate for power generation [35]. This large source of energy has made wastewater treatment facilities appealing to be explored as net-zero energy and even energy positive facilities [36][37]. Moreover, an installed biogas storage tank in a wastewater treatment plant can be leveraged for providing additional source of flexibility.

Battery storage technologies also have applications for flexibility. For example, Irvine Ranch Water District worked with its electric utility, Southern California Edison, to deploy a 6.25MW/ 35.7MWh network of battery arrays at its water facilities, which include six water treatment, water recycling, and pumping facilities. This battery system allows the water utility to buy and store energy during cheap electricity rate periods and consume stored energy to power its operations during periods when electricity rates are high. In addition, battery storage systems provide a source of stored power for Southern California Edison to depend on when the electric grid constrained or during demand response events [38].

V. CHALLENGES AND OPPORTUNITIES

The growth of renewable energy deployment has increased the need for flexible demand-side management resources that can help to maintain reliability for the electric grid and improve clean energy utilization for climate change mitigation, especially in absence of large-scale battery storage. This paper showed that the emissions benefits of load shifting strategies can be considerable and that flexibility strategies in the water industry have large opportunities for coordinating water and energy systems to derive synergistic benefits. However, several factors complicate active engagement of the water industry with the electric grid. Future research efforts should focus on:

- Executing more pilot experiments to help to identify and address the technical limitations of implementing flexible operation strategies to ensure that quality of water services is not compromised.
- Building a better understanding of the trade-offs and synergies across different energy management measures, in order to maximize overall demand-side management benefits. Developing this understanding offers a paradigm shift from traditional energy management strategies, which focus on energy efficiency interventions, to modern multi-purpose system-efficiency interventions, which prioritize the mitigation of greenhouse gases and other environmental impacts.
- Designing reasonable rate structures and demand-side management programs that better reflect the electric grid’s needs and can support rational energy management decision making in the water industry. Comprehensive models are needed that integrate water and energy systems to inform the value of flexibility for both the water industry and the electric grid. These models can guide the design of more effective market mechanisms to incentivize the water industry to take part in electric grid services.

ACKNOWLEDGMENT

This research study was financially supported by the Electric Power Research Institute (Award ID: 00 - 10007871), the National Science Foundation (NSF CAREER Award: Coordinating climate change mitigation and adaptation strategies across the energy-water nexus: An integrated research and education framework; CBET 1845931).

REFERENCES

[1] California ISO. What the duck curve tells us about managing a green grid 2016:1–4.

[2] Headley AJ, Copp DA. Energy storage sizing for grid compatibility of intermittent renewable resources: A California case study. Energy 2020;198:117310. doi:10.1016/j.energy.2020.117310.

[3] Sepulveda NA, Jenkins JD, de Sisternes FJ, Lester RK. The Role of Firm Low-Carbon Electricity Resources in Deep Decarbonization of Power Generation. Joule 2018;2:2403–20. doi:10.1016/J.JOULE.2018.08.006.

[4] Lund PD, Lindgren J, Mikkola J, Salpakari J. Review of energy system flexibility measures to enable high levels of variable renewable electricity. Renew Sustain Energy Rev 2015;45:785–807. doi:10.1016/J.RSER.2015.01.057.

[5] de Chalendar JA, Taggart J, Benson SM. Tracking emissions in the US electricity system. Proc Natl Acad Sci U S A 2019;116:25497–502. doi:10.1073/pnas.1912950116.

[6] CAISO. California ISO - Todays Outlook n.d. http://www.caiso.com/TodaysOutlook/Pages/default.aspx (accessed August 17, 2020).

[7] Gils HC. Economic potential for future demand response in Germany – Modeling approach and case study. Appl Energy 2016;162:401–15. doi:10.1016/J.APENERGY.2015.10.083.

[8] Kirchem D, Lynch M, Bertsch V, Casey E. Modelling demand response with process models and energy systems models: Potential applications for wastewater treatment within the energy-water nexus. Appl Energy 2020;260:114321. doi:10.1016/j.apenergy.2019.114321.

[9] Alstone P, Potter J, Piette MA, Schwartz P, Berger MA, Dunn LN, et al. 2025 California Demand Response Potential Study - Charting

California's Demand Response Future: Final Report on Phase 2 Results. 2017.

[10] Sanders KT, Webber ME. Evaluating the energy consumed for water use in the United States. Environ Res Lett 2012;7:034034. doi:10.1088/1748-9326/7/3/034034.

[11] Molinos-Senante M, Sala-Garrido R. Energy intensity of treating drinking water: Understanding the influence of factors. Appl Energy 2017;202:275–81. doi:10.1016/J.APENERGY.2017.05.100.

[12] Gustaf Olsson. Water and Energy: Threats and Opportunities. IWA Publishing; 2015.

[13] Electric Power Research Institute. Electricity Use and Management in the Municipal Water Supply and Wastewater Industries 2013:1–194.

[14] Copeland C, Carter NT. Energy-Water Nexus: The Water Sector's Energy Use. 2017.

[15] Deoreo WB, Mayer PW, Martien L, Hayden M, Funk A, Kramer-Duffield M, et al. California Single Family Home Water Use Efficiency Study. 2011.

[16] Takahashi S, Koibuchi H, Adachi S. Water Supply Operation and Scheduling System with Electric Power Demand Response Function. Procedia Eng 2017;186:327–32. doi:10.1016/J.PROENG.2017.03.257.

[17] van Staden AJ, Zhang J, Xia X. A model predictive control strategy for load shifting in a water pumping scheme with maximum demand charges. Appl Energy 2011;88:4785–94. doi:10.1016/J.APENERGY.2011.06.054.

[18] Paterakis NG, Erdinç O, Catalão JPS. An overview of Demand Response: Key-elements and international experience. Renew Sustain Energy Rev 2017;69:871–91. doi:10.1016/J.RSER.2016.11.167.

[19] Oikonomou K, Parvania M, Khatami R. Optimal Demand Response Scheduling for Water Distribution Systems. IEEE Trans Ind Informatics 2018;14:5112–22. doi:10.1109/TII.2018.2801334.

[20] Zimmermann B, Gardian H, Rohrig K. Cost-optimal flexibilization of drinking water pumping and treatment plants. Water 2018;10. doi:10.3390/w10070857.

[21] Diaz C, Ruiz F, Patino D. Modeling and control of water booster pressure systems as flexible loads for demand response. Appl Energy 2017;204:106–16. doi:10.1016/j.apenergy.2017.06.094.

[22] Berkeley Lab. Download Page for the 2025 California Demand Response Potential Study | Building Technology and Urban Systems Division n.d. https://buildings.lbl.gov/download-page-2025-california-demand-response (accessed August 18, 2020).

[23] CAISO. Managing Oversupply. Calif Indep Syst Oper n.d. http://www.caiso.com/informed/Pages/ManagingOversupply.aspx (accessed August 29, 2020).

[24] Blanke A. 2019 Q3 Report on Market Issues and Performance. CAISO 2019. http://www.caiso.com/Documents/2019ThirdQuarterReportonMarketIssuesandPerformance.pdfhttp://www.caiso.com/market/Pages/MarketMonitoring/AnnualQuarterlyReports/Default.aspx (accessed August 27, 2020).

[25] Shoreh MH, Siano P, Shafie-khah M, Loia V, Catalão JPS. A survey of industrial applications of Demand Response. Electr Power Syst Res 2016;141:31–49. doi:10.1016/j.epsr.2016.07.008.

[26] Menke R, Abraham E, Parpas P, Stoianov I. Extending the Envelope of Demand Response Provision through Variable Speed Pumps. Procedia Eng 2017;186:584–91. doi:10.1016/j.proeng.2017.03.274.

[27] Kirchem D, Lynch M, Bertsch V, Casey E. Market Effects of Industrial Demand Response and Flexibility Potential from Wastewater Treatment Facilities. 15th Int. Conf. Eur. Energy Mark., IEEE; 2018, p. 1–6. doi:10.1109/EEM.2018.8469974.

[28] Cherchi C, Badruzzaman M, Oppenheimer J, Bros CM, Jacangelo JG. Energy and water quality management systems for water utility's operations: A review. J Environ Manage 2015;153:108–20. doi:10.1016/j.jenvman.2015.01.051.

[29] Schäfer M, Hobus I, Schmitt TG. Energetic flexibility on wastewater treatment plants. Water Sci Technol 2017;76:1225–33. doi:10.2166/wst.2017.308.

[30] Kiliccote S, Olsen D, Sohn MD, Piette MA. Characterization of demand response in the commercial, industrial, and residential sectors in the United States. Wiley Interdiscip Rev Energy Environ 2016;5:288–304. doi:10.1002/wene.176.

[31] Bennett R, Bonkowski T, Martinez M, Pasmore J, Rivers D, Park L, et al. Southern California Edison-Irvine Ranch Water District Water-Energy Pilot, Phase 1 Report. 2017.

[32] Rouholamini M, Wang C, Miller CJ, Mohammadian M. A Review of Water/Energy Co-Management Opportunities. 2018 IEEE Power Energy Soc. Gen. Meet., IEEE; 2018, p. 1–5. doi:10.1109/PESGM.2018.8586013.

[33] Corcoran L, Coughlan P, McNabola A. Energy recovery potential using micro hydropower in water supply networks in the UK and Ireland. Water Sci Technol Water Supply 2013;13:552–60. doi:10.2166/ws.2013.050.

[34] Gude VG. Energy and water autarky of wastewater treatment and power generation systems. Renew Sustain Energy Rev 2015;45:52–68. doi:10.1016/J.RSER.2015.01.055.

[35] EPA. Opportunities for Combined Heat and Power at Wastewater Treatment Facilities: Market Analysis and Lessons from the Field. 2011.

[36] Yan P, Qin R, Guo J, Yu Q, Li Z, Chen Y, et al. Net-Zero-Energy Model for Sustainable Wastewater Treatment. Environ Sci Technol 2017;51:1017–23. doi:10.1021/acs.est.6b04735.

[37] Maktabifard M, Zaborowska E, Makinia J. Achieving energy neutrality in wastewater treatment plants through energy savings and enhancing renewable energy production. Rev Environ Sci Biotechnol 2018;17:655–89. doi:10.1007/s11157-018-9478-x.

[38] Beeman B, Franecki D, Sorrentino C. Irvine Ranch Water District and Macquarie Capital announce completion of the largest behind-the-meter energy storage project in the U.S. 2018.