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Authors
Berger, Michael A.
Hans, Liesel
Piscopo, Kate
et al.

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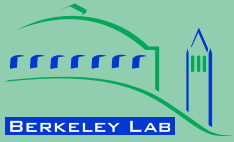
Exploring the Energy Benefits of Advanced Water Metering

Michael A. Berger, Liesel Hans, Kate Piscopo, and Michael D. Sohn

Energy Analysis and Environmental Impacts Division
Energy Technologies Area

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ABSTRACT

Recent improvements to advanced water metering and communications technologies have the potential to improve the management of water resources and utility infrastructure, benefiting both utilities and ratepayers. The highly granular, near-real-time data and opportunity for automated control provided by these advanced systems may yield operational benefits similar to those afforded by similar technologies in the energy sector. While significant progress has been made in quantifying the water-related benefits of these technologies, the research on quantifying the *energy* benefits of improved water metering is underdeveloped. Some studies have quantified the embedded energy in water in California, however these findings are based on data more than a decade old, and unanimously assert that more research is needed to further explore how topography, climate, water source, and other factors impact their findings. In this report, we show how water-related advanced metering systems may present a broader and more significant set of energy-related benefits. We review the open literature of water-related advanced metering technologies and their applications, discuss common themes with a series of water and energy experts, and perform a preliminary scoping analysis of advanced water metering deployment and use in California. We find that the open literature provides very little discussion of the energy savings potential of advanced water metering, despite the substantial energy necessary for water's extraction, conveyance, treatment, distribution, and eventual end use. We also find that water AMI has the potential to provide water-energy co-efficiencies through improved water systems management, with benefits including improved customer education, automated leak detection, water measurement and verification, optimized system operation, and inherent water and energy conservation. Our findings also suggest that the adoption of these technologies in the water sector has been slow, due to structural economic and regulatory barriers. In California, we see examples of deployed advanced metering systems with demonstrated embedded energy savings through water conservation and leak detection. We also see substantial untapped opportunity in the agricultural sector for enabling electric demand response for both traditional peak shaving and more complex flexible and ancillary services through improved water tracking and farm automation.

Keywords: water resources management, advanced metering infrastructure, water-energy nexus, energy services

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Abbreviations

AB	Assembly Bill
ADR	Automated demand response
AMI	Advanced metering infrastructure
AMR	Automatic meter reading
AS	Ancillary services
AWWA	American Water Works Association
BG	Billion gallons
CEC	California Energy Commission
CPUC	California Public Utilities Commission
DCU	Data collection unit
DR	Demand response
DWR	Department of Water Resources
EBMUD	East Bay Municipal Utility District
GPM	Gallons per minute
GW	Gigawatt
HEM	Home energy management
IHD	In-home display
IOU	Investor owned utility
kWh	Kilowatt hour
LBNL	Lawrence Berkeley National Laboratory
MG	Million gallons
MIU	Meter interface unit
MNF	Minimum nighttime flow
MTU	Meter transmission unit
M&V	Measurement and verification
MW	Megawatt
NRW	Non-revenue water
PUC	Public Utilities Commission
RF	Radio frequency
SB	Senate Bill
SCADA	Supervisory Control And Data Acquisition
SWP	State Water Project (of California)
TOU	Time-of-use
US DOE	United States Department of Energy
VFD	Variable frequency drive

Glossary of Terms

Advanced Metering Infrastructure (AMI): A technology system that connects customer meters to the utility through a bi-directional communication network, such as telephone wires or radio frequency transmission, and stores and analyzes the collected data in a central database. Utilities can collect meter data at frequent intervals, relay that data to customers, and have additional capabilities (e.g. remote shutoff) depending on the system configuration.

Automatic Meter Reading (AMR): A technology system by which a utility can digitally collect and store meter readings. Data can be communicated through hand-held data-loggers, radio frequency transmission, or telephone wires. Does not allow two-way communication between utility and meters.

Municipal Water System: The infrastructure that extracts, conveys, and treats water for use in the residential and commercial sectors. Some industrial customers are part of the municipal system, however the majority self-supply water (Maupin et al. 2014).

Embedded Energy of Water: The amount of energy used to collect, convey, treat, and distribute water to end users, and the amount of energy used to collect, transport, and treat wastewater.

1   Introduction

This report identifies the ways in which advanced water metering is being used to enable energy benefits and highlights what the research suggests to be prominent areas of future opportunity. This report is the synthesis of a comprehensive literature review, interviews with subject matter experts, and original analyses. *Section 1* provides historical context of the water-energy nexus and water development, defines commonly used terminology, and describes the methods used. *Section 2* is an in-depth discussion of the opportunities for energy benefits afforded by improved water metering. *Section 3* highlights barriers and challenges to realizing these energy benefits. *Section 4* explores the scale of opportunities and the barriers to realizing the energy benefits of advanced water metering in California through a high-level quantitative analysis and discussion. *Sections 5 and 6* provide concluding remarks and recommendations for future work.

1.1   Methods and Scope

This report covers three broad efforts. Our first task was a literature review of three primary areas: (1) the water-energy nexus; (2) advanced metering in both the energy and water sectors; and (3) applications of synergistic water-energy activities enabled by improved data collection and system control, which includes applying water-related data to provide energy benefits (e.g., energy efficiency).

Our second task was to gain an appreciation of the current state of practice by interviewing experts from academia, industry, utilities, and regulatory bodies. We interviewed two academic researchers, two researchers from independent industry think tanks, engineers at a facilities department of a large college campus, members of a state public utilities and services commission, senior engineers at a municipal utility responsible for providing both water and energy, an operations expert at a utility-focused software company, and a senior advisor at an agricultural sensors company. Due to the recent demand for research, technical expertise, and market solutions in the water-energy space in the Southwestern United States, four of these experts are from California and two are from the Rockies. Another is from the Midwest, and two are based on the East Coast.

Lastly, we present a scoping study and follow-on discussion of the energy benefits of advanced water metering in California. We chose California as a case study because there exists momentum for tackling water-energy issues from regulators, industry, and consumers. The significant four-year drought affecting much of the American Southwest, particularly California, has motivated a broad interest in implementing improved water metering. We therefore anticipate the availability of a relatively large amount of water-energy data from pilot studies in the near future. Finally, we see increased activities from

regulators and other agencies, including the California Public Utilities Commission (CPUC) and the California Energy Commission (CEC), to tackle resource use efficiency matters.

This research focuses primarily on the municipal and agricultural sectors. We surveyed industrial applications of water metering for energy benefits, and concluded that most industries for which energy and water are variable costs have internalized and attempted to optimize their processes. Additionally, industrial applications vary widely in geography and process, making high-level scoping and assessment unwieldy. For these reasons, further discussion of advanced water metering for energy benefits in the industrial sector has been left to those industry experts better suited to additional, tailored analyses.

1.2   The Water-Energy Nexus

Peter Gleick's seminal 1994 report, "Water and Energy", set the foundation for understanding how water and energy systems are fundamentally interconnected. Over the last two decades, the water-energy nexus has gained attention due to local, regional, national, and global concerns regarding energy security, water scarcity, and the impacts of global climate change. For example, the historic 2012-2015 North American Drought impacted electricity generation capacity by restricting surface water withdrawals used for power plant cooling, as well as drastically reducing hydropower resource availability (Pulwarty 2013). Situations such as this highlight how water and energy systems are inextricably linked and the potential vulnerabilities this creates. Work has also been done to quantify the magnitude of the links between water and energy systems, exemplified by Figure 1.

As a result of the growing appreciation of how interconnected water and energy systems are, the United States Department of Energy (US DOE) has identified areas in need of proactive and improved joint system optimization and management (US DOE "The Water-Energy Nexus"). In addition, US DOE has invested in extensive research on technologies that can improve the energy efficiency of water systems or reduce the use of water during energy production, as well as policies to enhance the effectiveness of joint systems management.
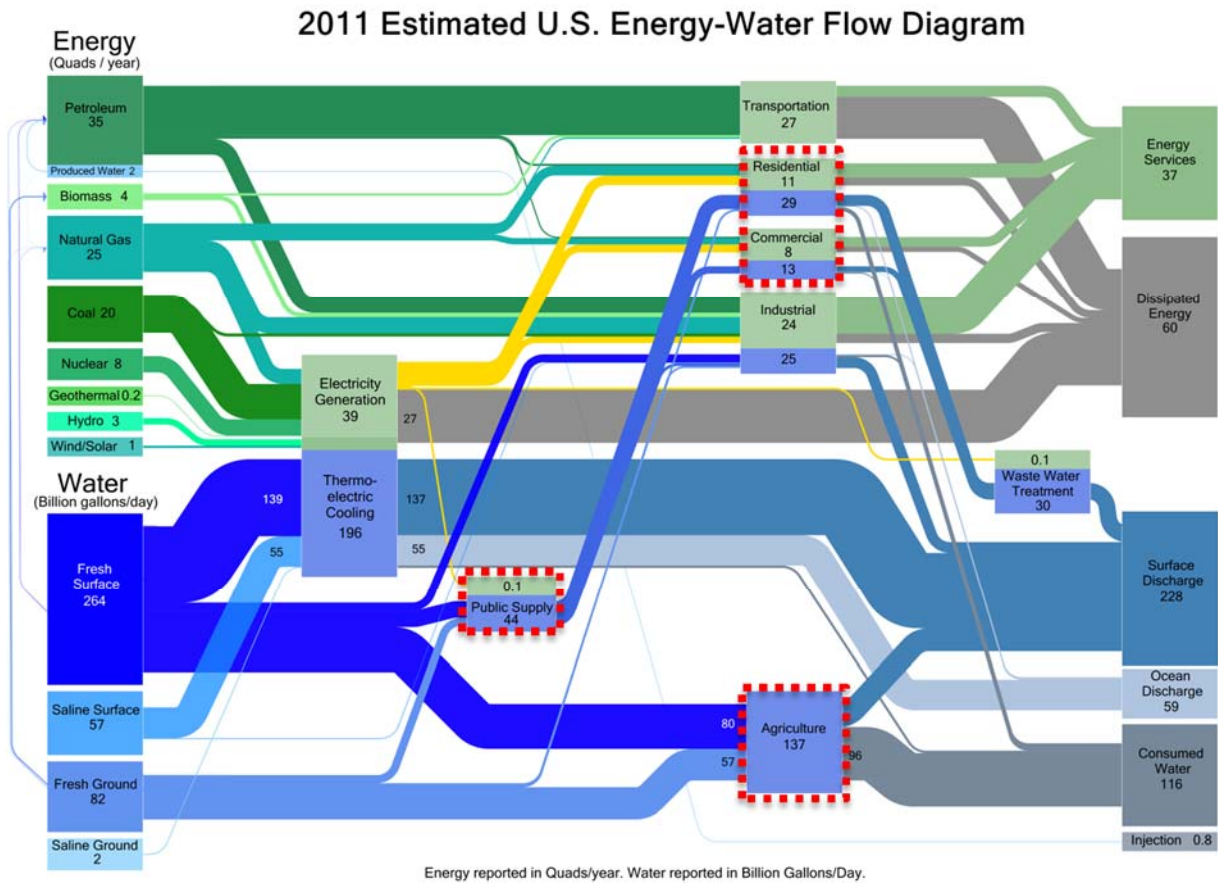
Figure 1: Energy-water flow diagram showing the major sources and sinks of both water and energy resources in the United States, using data from 2011 (US DOE "The Water-Energy Nexus"). Sectors discussed in this report are outlined in red.

The literature regarding "energy for water" systems lacks a set of agreed upon definitions for common terms and metrics necessary for quantitative discussion. Terms including "energy intensity," "associated energy," "embodied energy," and "embedded energy" are often used interchangeably and without formal definition. The terminology used throughout this report is "embedded energy," and has the following definition.

> *"Energy Embedded in Water" refers to the amount of energy that is used to collect, convey, treat, and distribute a unit of water to end users, and the amount of energy that is used to collect and transport used water for treatment prior to safe discharge of the effluent in accordance with regulatory rules. (GEI Consultants and Navigant Consulting 2010)*

It is important to note that "embedded energy" specifically and intentionally excludes the energy use associated with water-related end uses (e.g., residential water heating), and is typically reported as an *amount of energy per unit of water* (kWh/gallon). End-use specific energy use is excluded for two reasons: (1) the focus of this report is on large-scale advanced water metering systems, which do not disaggregate end-use level water and energy use; and (2) the energy needed for specific water-related end uses deserves detailed research on a technology-by-technology and end-use-by-end-use basis, and is outside the scope of this study.

Additionally, "energy intensity" will be used throughout this report in reference to the amount of energy required per unit of water for *individual segments* (e.g., wastewater treatment) of the water system.

1.2.1   Embedded Energy of Water

The embedded energy of a given unit of water is highly dependent upon the location, underlying topography of the water infrastructure, and water source (deMonsabert et al. 2009). For example, a 2005 CEC report on water-related energy use found that the average embedded energy for Northern and Southern California was 4,000 and 12,700 kWh/MG, respectively, with even greater spread in embedded energy values due to local system characteristics (CEC 2005). Additionally, the energy needed for providing water can be a signification portion of all energy use, with the CEC's report estimating that 5% of energy consumption in California can be attributed to the conveyance, distribution, and treatment of water.

Improved water flow, pressure, and leakage data collection, enabled by advanced water metering technologies, could better characterize the embedded energy in water systems, which in turn could help identify and prioritize research and development opportunities to tap large potential efficiency gains for both water and energy. Targeting water-energy programs in areas where the embedded energy is highest, for instance, is more likely to result in significant energy savings than programs in areas where the embedded energy of the water system is low. In order to fully capitalize on these potential savings, however, more information about the energy intensity of individual processes (e.g., freshwater treatment), how that energy intensity differs by geography and topography, and the temporal differences in energy intensity is needed (US DOE "The Water Energy Nexus").
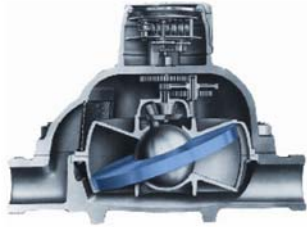
1.3 Advanced Water Metering

Since the development of the first commercial mechanical water meter in the 1850s (Walski 2006), water-metering technology has steadily improved in precision, accuracy, and reliability. However, only recently have communications technologies improved and become cost-effective enough to change how the data generated by these meters are collected. Table 1 outlines the common volumetric and leak detection meter technologies, and Table 2 outlines the communications components that relay the meter data.

Traditionally, customer-level metering requires water utility employees to physically visit individual customer sites on a semiannual or monthly schedule to read the water meter's logger, which only provides the total volume of water that has been used since the last reading, and has to be manually entered into a central database for billing purposes. Given the time and labor involved, the traditional operating model is an expensive process through which customers and utilities gain very little knowledge of the temporal aspects of customer water use. As such, recent advancements in metering and communications technologies have resulted in drastically improved, more integrated methods of metering, communication, data storage, and analytics. Two technologies to have major impacts on water metering infrastructure are automatic meter reading (AMR) and advanced metering infrastructure (AMI).

AMR is a system in which the customer meters are able to send consumption data at regular intervals through communication infrastructure such as radio frequency (RF) or telephone wires. Not only does AMR allow for more frequent data collection, but most AMR systems also eliminate the need for utility employees to visit individual sites. However, it does not allow two-way communication between the meters and the utility (e.g., the utility cannot remotely tell the meter to change recording behavior). For this reason, meters in an AMR system are not considered "smart" meters and are primarily used in the water sector to reduce the labor cost of data collection. Improved meter accuracy and standardizing meter inventories are additional benefits (Koo et al. 2015).

Table 1: Summary of common water metering technologies.

Metering Technology	Description	Normal Operating Range
Mechanical 1	Uses either positive displacement or velocity-based methods to measure volume of water consumed. The overwhelming majority of utility meters are mechanical, and they are typically used for residential and commercial billing purposes.	Nutating Disk: 0.25-170 GPM[2] Oscillating Piston: 1-50 GPM[3] Multi-jet Impeller: 1-100 GPM[4]
Static 5	Uses static measurement methods, such as magnetic or acoustic flow sensors, to measure velocity of water flow, and then compute volumetric water consumption. Much newer than mechanical meters, static meters have been used in industrial and commercial settings, but are increasingly common for residential applications.	Ultrasonic: 0.05-160 GPM[6] Magnetic: 0.7-180 GPM[7]
Compound 8	Incorporates multiple measurement technologies, typically one technology that performs well at high flows, and one that performs well at low flows. Typically used for commercial or multi-family residential applications.	0.5-4000 GPM[8,9]
Acoustic Leak Detection 10	Deployed on water distribution infrastructure, these sensors use sound waves to measure flow levels during the night, when ambient noise and demand are lowest, and then relays the data to the central server for analysis.	N/A
1 Niagra Meters, "Nutating Disc" 2 Badger Meter, "Recordall® Disc Series Meters" 3 Sensus, "accuSTREAMTM Meters" 4 RG3 Meters, "Multi-Jet – Bottom Load –Meters" 5 Sensus, "AccuMAGTM Water Meters"	6 Badger Meter, "E-Series® Ultrasonic Meters" 7 Sensus, "accuMAGTM Meters" 8 Zenner Performance, "Compound Meters" 9 Badger Meter, "Recordall® Compound Series Meters" 10 Sensus, "Permalog+ Acoustic Monitoring Sensor"	

AMI is the natural extension of AMR technology, with more sensor integration, two-way communication, system controls, and real-time analytics. Water AMI consists of "smart" water meters that measure the volume of water transferred between locations and reports this information through bi-directional communication with the system's communications infrastructure. This volumetric transaction is typically only recorded when a utility transfers water from its ownership to a building operator, such as when the water crosses

a utility meter, however it can also be recorded within a utility's distribution infrastructure as a means of monitoring flows (Janković-Nišić et al. 2004). These smart water meters give the utility more capabilities, including flexible data recording, real-time analytics like leak-detection, and remote shutoff (e.g., in the case when a large leak is detected). The data generated by the smart water meters is collected and relayed through a range of communications infrastructures (e.g., RF, telephone wires) to the utility's central server, where data is cleaned, analyzed, and stored.

Table 2: Summary of common advanced water metering communications technologies.

Communications Technology	Description	Functionality
Meter Register	Translates mechanical or solid-state meter signals into volumetric reading. Displays this information visually, stores it for collection, or transmits it to an Meter Interface Unit (MIU) or Meter Transmission Unit (MTU).	Depends greatly on the register type. Minimum resolutions as low as 1 gallon.
Meter Interface Unit (MIU) or Meter Transmission Unit (MTU)	Collects readings from individual meter registers and communicates them, along with timestamp information, to a Data Collection Unit (DCU). Some can also accepts signals from AMI network.	Typically collects data at intervals between 15 minutes and 1 day.*
Data Collection Unit (DCU)	Collects and transmits data from multiple MIU/MTUs. Technology and use cases vary greatly. In fixed network systems, they are often mounted on telephone poles, and communicate via radio. In "handheld" AMR systems DCUs are small handheld devices that communicate with meters via touch or radio.	Some DCUs store collected data (28 days or 600,000 transmissions[4]), but many simply relay data from MIU/MTUs to central storage and processing servers.

* Most advanced meters can collect and transmit readings on command, and therefore the frequency at which consumption is measured is dictated by the utility's needs and data management and analytics capabilities.

1 Badger Meter, "Recordall® Transmitter Register" 3 Sensus, "Standard FlexNet® Base Stations"
2 Badger Meter, "ORION® Cellular Endpoint" 4 Aclara, "STAR Network DCU II"

In addition to customer-level metering technology, all water utilities implement some level of Supervisory Control And Data Acquisition (SCADA) systems. SCADA is a remote monitoring and control system that operates in real-time to automate and assist the management of treatment and pumping processes. SCADA systems monitor and control water and wastewater treatment plants, measuring a number of important process characteristics, including inflows and outflows, treatment status, and water temperature. SCADA systems do not inherently store and analyze past data, however some newer systems are capable of being integrated with more advanced analytical tools (Cherchi et al. 2015).
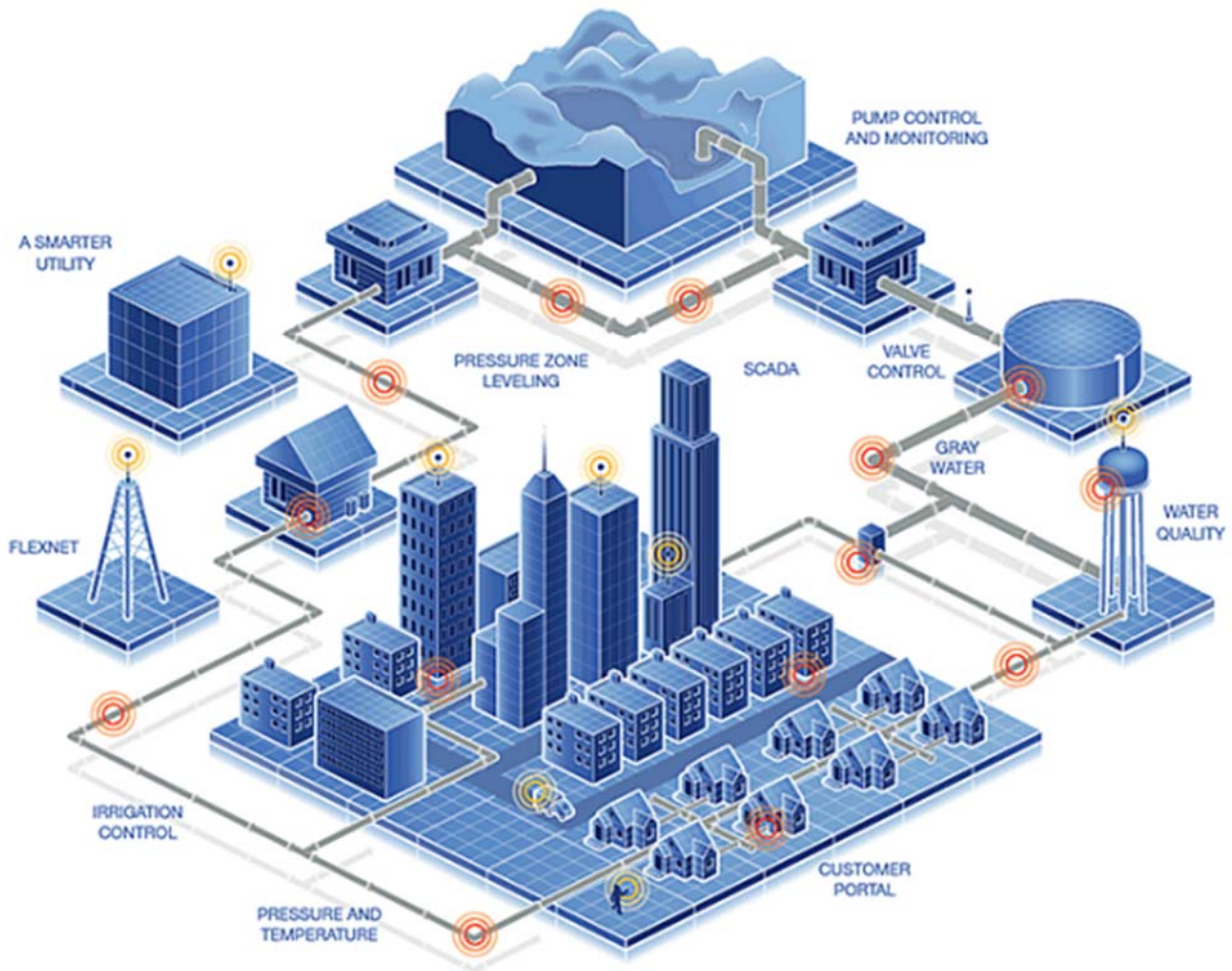
Figure 2: High-level diagram of advanced water metering system (Sensus 2016). Basic AMI systems include a subset of the shown functionality, and include, at a minimum, smart water meters, a customer portal, and centralized data collection and processing.

The water industry is trending towards AMI and more advanced SCADA infrastructure (Laughlin 2003; Turner 2005). Figure 2 shows a diagram of an advanced metering, sensors, and controls system and its many components and capabilities. This wide range of data

collection, controls, and analytics capabilities allow water utilities to utilize advanced metering systems to reduce water loss through improved leak detection (Britton et al. 2013), reduce operating costs through streamlined billing (Beal and Flynn 2015), implement volumetric rate structures to incentivize water conservation (Borisova et al. 2014), and utilize high-frequency, near real-time data for a various strategic system management efforts (Stewart et al. 2013). End users benefit from behind-the-meter leak detection and detailed information about their water consumption, both of which can lead to more efficient water use and lower water bills (Britton et al. 2013). More generally, advanced water metering provides more transparent information about where, when, and how water is consumed, which can enable conservation and greater efficiency (Pacific Institute 2014). Finally, while water AMI systems have demonstrated significant water conservation (Ritchie 2015), their value as an energy-saving tool has not yet been thoroughly explored.

2 Energy Benefits of Advanced Water Metering

In this section, we will report on the current state of water AMI in the municipal and agricultural sectors, its market penetration, and its current applications for energy savings and benefits. It is important to note that quantifying, comparing, and prioritizing these energy opportunities must be done on a case-by-case basis as a part of the cost-benefit analysis for an advanced water metering system such as AMI.

2.1 Embedded Energy Savings

2.1.1 Water Conservation Through Altered Behavior

Studies have demonstrated that information provided by advanced metering of energy and water can encourage behavioral reductions in consumption by increasing consumer knowledge about their resource use. Web portals, text message alerts, and In-Home Displays (IHDs) are examples of communications platforms used to make resource consumption more transparent to consumers. In the energy sector, Faruqui et al. found that IHDs that display the near-real-time information about home energy use collected by smart meters can reduce energy use by 7% (2010). Bariss et al. found that a smart electricity meter rollout to 1,000 customers in Latvia resulted in an average 19% decrease in electricity consumption compared to a control group (2014). Finally, a meta-analysis of research on "feedback" mechanisms, which includes improved billing, advice, and real-time usage data, and their impacts on residential electricity usage found that feedback can provide savings between 4 and 12% (Ehrhardt-Martinez et al. 2010).

A similar opportunity is present in the water sector. Implementing advanced water metering systems and providing users with much more granular, real-time data on water consumption can result in water conservation. For example, a 2013 paper by Fielding et al. explore the impact of customer-specific water use information on consumption patterns, and find that daily consumption data from smart water meters can reduce water consumption by an average of 9%. Additionally, a 2014 pilot study at East Bay Municipal Utility District (EBMUD), which supplies water throughout the San Francisco East Bay, installed water AMI systems that provided hourly water consumption data (in units of tenths of a gallon per hour) to customers through an online web portal. EBMUD found water savings between 5-50%, with an average of 15%, among residential customers after the installation of the savings, while noting that some of these savings are likely due to customer-side leak repair (EBMUD 2014). When consumers use less water, the embedded energy necessary to provide that water is avoided, as the water utility needs to extract, treat, and distribute less water, reducing the energy demands of the water utility. Unfortunately, very few studies quantify the embedded energy reductions attributable to these water reductions.

2.1.2   Leak Detection and Repair

As water infrastructure is typically located underground, water main degradation and damage from soil pressure, excavation and construction threats, tree root growth, freeze-thaw cycles, and earthquakes are common occurrences. The resulting water leakage from water mains into the surrounding soil are called "physical losses" and are not only difficult to detect, but also represent a major source of water loss, known as non-revenue water (NRW), that utilities cannot financially recover or bill to customers. Another source of NRW are "commercial losses", which consist of water that flows *into* a water system but is not correctly accounted for flowing *out* of the system. Commercial losses are the result of faulty or inaccurate meters, data handling errors, or water theft. NRW is calculated using Equation (1).

$$(1) \qquad NRW\ \% = \frac{\text{System Input Volume} - \text{Billed Authorised Consumption}}{\text{System Input Volume}} \times 100\%$$

While commercial losses do not have associated energy impacts, physical losses represent real wasted energy in the form of embedded energy and associated GHG emissions. A typical rule of thumb estimate for physical water losses is 10-15% in the U.S. and can be higher in different parts of the country and the world (Hering et al 2013). Figure 3 shows the distribution of NRW, as a fraction of total water inputs, for utilities in The International Benchmarking Network for Water and Sanitation Utilities (IBNET) database, which compiles water utility data from around the world. One can see that over 15% of utilities in the IBNET database had NRW fractions over 50% in 2006.
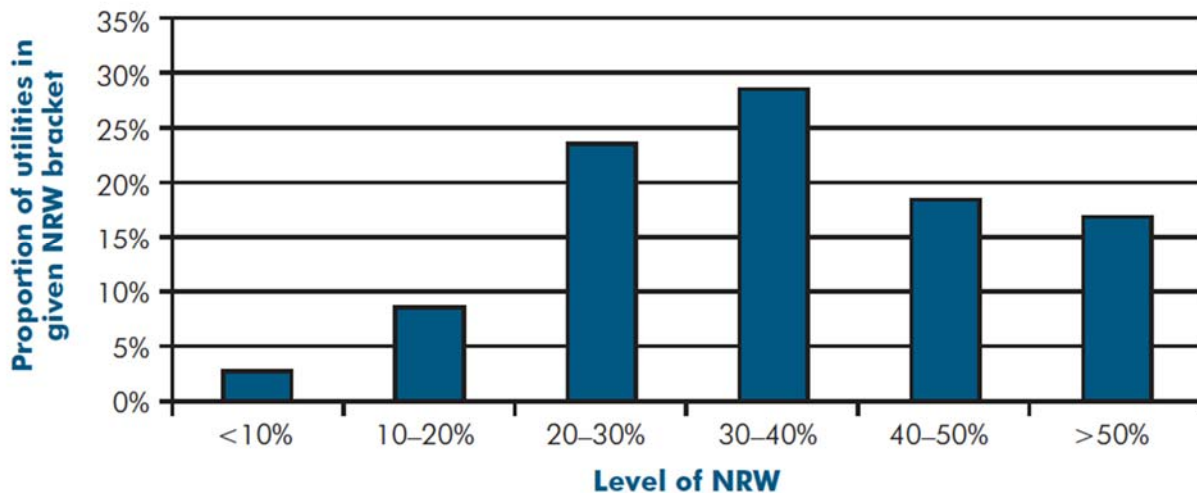

Figure 3: Non-Revenue Water performance of utilities in The International Benchmarking Network for Water and Sanitation Utilities (IBNET) database (Kingdom et al. 2006).

In the United States, it was estimated that 5-10 billion kWh/year of electricity is associated with NRW, which is approximately 6-13% of all electricity used by water agencies annually (AWWA Water Loss Control Committee 2003). The World Bank estimates that 80% of NRW in developed countries is due to real losses, which means approximately 4-8 billion kWh/year of electricity is wasted through leaks in the U.S. For perspective, that is enough electricity to power 360,000-720,000 households annually (EIA 2015). These leaks occur on "both sides of the meter," meaning on the customer's side (e.g. in homes) and on the utility's side (e.g. in water distribution infrastructure). On the whole, the following discussion of the available literature suggests that a substantial fraction of the wasted electricity associated with leaks could be saved through leak detection enabled by advanced municipal water metering.

Customer-Side Leak Detection

The recent DeOreo et al. report, "Residential End Uses of Water, Version 2", found that leaks account for 13% of all residential indoor water consumption across the U.S. (2016). Customer-side leaks can be detected through a number of methods, including water audits and analysis of water consumption data that range in complexity but are greatly improved when coupled with an AMI system. One water provider in Queensland, Australia analyzed hourly consumption data for all 22,000 of their residential customers and identified approximately 800 households that had continuously used water for 48 straight hours, indicating a highly likelihood of leaks. After providing a subset of these customers with extensive analysis of their minimum nighttime flow (MNF) values to communicate the presence of leaks, the water provider saw an 89% reduction in MNF within the subset (Britton et al. 2013). The City of Sacramento, California, began implementing a water AMI system in 2009. After installing 17,600 smart water meters, they monitored their performance from 2010-2011. Through analysis of the volumetric consumption data collected, 1,076 leaks were identified, 75% of which were verified in the field. The City estimated that fixing these leaks saved an estimated 236 million gallons of water over the two-year period, or approximately 12.6 gallons per capita per day (California DWR 2013).EBMUD has completed eight water AMI pilot projects throughout their residential service area, including an acoustic leak detection system. The AMI systems communicate hourly consumption data with residential customers via a web portal, which sends customers notifications when consumption patterns indicate a suspected leak. Preliminary results from these pilot projects indicate that these systems have been effective at identifying "a surprising number of leaks" (EMBUD 2014), and EBMUD has since requested further information from vendors regarding current AMI system capabilities (EBMUD 2015).

Utility Infrastructure Leak Detection

Experts have identified that daily water system operations could be drastically improved with better data (Tarroja et al. 2016). By augmenting current operational models and procedures, largely based on SCADA system data, with water AMI data, experts suggested that the development and application of advanced algorithms to quickly and accurately detect leaks could realize substantial operational cost savings. These analytical capabilities could enable water utilities to take preventative measures by identifying minor leaks before they become expensive catastrophic pipe failures. However, utility-side leak detection is typically more complex than customer-side detection, primarily due to the number of inputs and outputs present in water distribution networks. A number of studies have proposed solutions to this technical problem. Zan et al. discuss how data from flow, pressure, and acoustic sensors can be analyzed with joint time-frequency analysis to diagnose leaks in a municipal distribution system (2014). Goulet et al. (2013) and Colombo et al. (2009) show different methods using flow and pressure data recorded at high frequency that could be adequate in providing leak detection. Loureiro et al. demonstrate how to leverage smart water meter data to perform water balances on district metered areas (discrete and distinct sections of water distribution infrastructure) in order to detect leaks (Loureiro et al. 2014). In the field, cities of Leesburg, Virginia and Monaca, Pennsylvania reduced their NRW from 15% to 7% and 50% to 15%, respectively, after installing AMI to diagnose and reduce distribution leaks (Richie 2015).

One of the rare studies that estimates embedded energy savings associated with water efficiency projects is ECONorthwest's 2011 study, "Embedded Energy in Water Pilot Programs Impact Evaluation", which analyzes 9 pilot programs implemented by California's three energy IOUs in collaboration with local water utilities. One of the report's key findings came from a Southern California Edison (SCE) leak detection program that utilized water audits, supported by volumetric water meter data, to identify leaks in water distribution infrastructure for three water agencies:

> *"SCE's Leak Detection program appears to offer the greatest energy savings potential (at relatively low cost) among all the Pilot programs. In particular, the energy savings documented in this report are based on leaks that were actually repaired during the program period; potential achievable water (and energy) savings were estimated to be much higher by the program implementation contractor."*

While this pilot program was not utilizing a "smart" water meter system, but rather performing analysis on historical data, it did demonstrate that the magnitude of energy savings associated with leak repair is significant. The estimated annual water and energy savings for this program are reported in Table 3.

Table 3: Estimated water and embedded energy savings from program-related leak repairs, and potential untapped savings (ECONorthwest 2011).

	Water (MG)	Energy –Agency (kWh)	Energy - All Sources (kWh)
Saved from Repairs	83	178,143	497,788
Potential Savings	263	583,277	1,662,621
Energy savings are shown for both the water agency (Energy – Agency), and from all sources (Energy – All Sources), which typically includes extraction or conveyance of water for which the agency is not responsible.			

Identifying leaks in distribution infrastructure before catastrophic pipe failures occur can save the utility time, money, and labor while also reducing the embedded energy required to provide water throughout the system. Although further research is needed to better quantify and compare the costs and benefits of using AMI, acoustic leak detection sensors, SCADA, or a combination, many technologies that can perform leak detection currently exist. Additional pilot tests on a larger scale could further improve our understanding of the barriers to adoption and optimal deployment strategies.

2.1.3   Energy Efficient Infrastructure Design and Operation

Currently, water infrastructure is designed to meet the flow requirements needed at absolute peak demand, and the absolute peak demand is computed using engineering estimates of maximum daily consumption and not necessarily on the analysis of historical consumption data. Pumps are selected to meet peak demand and are not operated in their optimal efficiency at typical demand flows. In effect, this means water infrastructure is overdesigned for the majority of demands, which may lead to inefficient operation and thus higher embedded energy of the water delivered by the system. This reliance on engineering best estimates of peak flows, rather than a consumption-data based design approach, could also be increasing the cost to build and maintain water infrastructure. Further research is needed on how best to integrate the wealth of highly granular water AMI data into system and infrastructure design practices.

Water infrastructure in the United States and throughout much of the world is quite old, and is therefore constantly being maintained, replaced, improved, and expanded to meet the growing needs of industry, rapidly urbanizing demographics, and a growing population. As water infrastructure is typically underground, repairing and replacing pipes is expensive. This situation presents opportunities to leverage the high-quality, high-resolution data from AMI systems to prioritize the repair and replacement of system

components. Since water utilities are often budget constrained and pipe replacement is done based on best-guess pipe "lifetime" schedules, it is not uncommon for utilities to spend hundreds of thousands or millions of dollars to excavate and replace pipes that are in good condition. This inefficiency could be reduced, and the embedded energy of the water system lowered due to lower water loss rates, if utilities had advanced water metering data to identify and prioritize leaking pipes for replacement rather than using traditional rule-of-thumb replacement periods.

Data about changes in water demand patterns, provided by AMI, could inform improved medium- to long-term water forecasting models. The improved accuracy of these AMI-supported models could provide utility operational managers the control, feedback, and monitoring capabilities to more readily alter conveyance and distribution pumping patterns. These models could also improve infrastructure redesign by identifying areas where the distribution network is over- or under-designed, ideally leading to more optimal sizing of pipes and pumps as well as improved siting of pumping, storage, and monitoring resources. More granular and real-time data about water consumption throughout a water district could also be better linked to the district's energy use, and help to quantify pump shifting opportunities for demand response or support the siting process for additional water storage infrastructure.

Additionally, pressure management of water distributions systems has been shown to lower overall leakage rates and energy use. Xu et al. found that reducing inlet pressure to a distribution system by 14% led to an 83% reduction in minimum night flow (MNF) and an associated savings of 62,633 cubic meters of water, 1.1×10^6 MJ of energy, and 68 tons of CO_2 equivalent greenhouse gas emissions per year per kilometer of pipe (2014). However, due to the variable nature of distribution system structure, operation, and water quality requirements, the authors observe that these results cannot be directly extrapolated to other systems. Pressure management approaches can be supported by improved water metering, through both SCADA and AMI systems, which may allow for lower operating pressures, though further research and demonstration work is needed before conclusions can be drawn.

2.2 Electric Load Management and Demand Response

Water infrastructure is a significant contributor to peak electrical demands on the grid, and therefore presents an opportunity for permanent load management and demand response (DR). For example, the California water supply alone is estimated to require 2-3 GW, or 3-5% of the state's total electricity demand, on peak days (Fujita et al. 2012; CEC 2005). Opportunities to shift or reduce the peak demand from the water sector could address peak system demand issues, potentially resulting in lower electricity prices and reducing the likelihood of demand exceeding capacity. Additionally, water is readily storable, and water

systems face different constraints than electrical systems, making water-related energy a potentially flexible and reliable DR resource. Improved water demand forecasting, enabled by advanced water metering, could support system operators and encourage customers to shift their water demands out of peak electricity demand periods.

2.2.1   The Municipal Sector

Olsen et al. estimate an average of approximately 1.1 GW of municipal pumping demand, which does not include large water conveyance systems, during summer months in the Western Interconnection, of which approximately 15 MW is readily available for DR (Olsen et al. 2013). While individual customers are far removed from the peak-electricity impacts of their water use, water utilities responsible for conveying, treating, and distributing water often face time-of-use (TOU) energy prices, which incentivizes them to minimize the costs associated with using energy during peak hours. Our interviews with water and energy utility experts, as well as observations from the literature, indicate that some utilities have implemented advanced water metering and water storage to help them shift some pumping and treatment to off-peak hours to reduce their energy costs (Fujita et al. 2012; Cherchi et al. 2015), while others participate in electric demand response programs (EPRI 2013). However, there are still very few reports that demonstrate and quantify examples of water-AMI-supported responsive load management.

On the customer side of the meter, increasing connectivity, epitomized by the Internet of Things (IoT) concept, will likely affect water-related energy consumption through behavior change and advanced home automation. A 2010 CEC study on residential peak electrical demand found that customers who were asked to minimize their water consumption during the electrical utility's on-peak period used approximately 50% less water during peak electricity hours as compared to a control group who was not provided this messaging (House 2010). If implemented across the water agency's total residential population, the study estimated the regional water district could reduce their peak electric load by 3 MW. The study proposed that a likely explanation of this reduction is consumers shifting lawn irrigation to evening or nighttime hours. Other examples of this sort of demand shifting flexibility include "smart" appliances, such as clothes washers and driers, connected through the IoT to a home energy management (HEM) system. Such HEM systems are capable of shifting appliance loads to off-peak hours with minimal effects on level of service. These types of home management systems can be expensive, but it is possible that integrating water management into a home energy and water management platform would provide co-benefits. For example, AMI-enabled pricing structures, such as time-of-use water prices, could increase the ability of these home management systems to capture value for the consumer.

2.2.2 The Agricultural Sector

The concept of joint energy and water management is becoming increasingly important in the agricultural sector, as growers make the switch from water inefficient flood irrigation to advanced water-efficient precision irrigation systems. Although modernized irrigation methods use much less water, they are typically more energy intensive due to the need to pressurize extensive piping systems. One study estimates that the modernization of Spain's irrigation systems from 1950 to 2007 reduced the water per hectare of farming by 21%, but increased the energy per hectare by 657% (Corominas 2010). Another study of two irrigation districts in Australia found that switching from gravity fed irrigation to pressurized irrigation could increase electricity intensities, in terms of energy per unit are(MJ/hectare), by 8-179% depending on crop type (Jackson 2009). As threats to water security grow, including a shifting climate and dwindling groundwater reserves, they accelerate the transition to water efficient irrigation systems, and the agricultural sector's energy demands are likely to increase. Olsen et al. estimate agricultural water pumping currently contributes 2.7 GW of load during summer months in the Western Interconnection, of which approximately 400 MW is reasonably available for DR (Olsen et al. 2013). Given this energy-water tradeoff, developing systems that improve the flexibility of agricultural water and energy demands are anticipated to be growing areas for both R&D and advanced water metering applications.

One method currently used in the agricultural sector is the practice of shifting water pumping to off-peak periods, when the demand on the electricity grid is lowest. Factors that limit the effectiveness of this demand management strategy are the total volume of water storage available in a system, the maximum capacity of pumps able to move water into a system after peak hours, water delivery schedules, and the uncertainty in water demand forecasting (Marks et al. 2013). This strategy can be used by individual farms that have on-site storage, but is often most cost-effective for irrigation districts. For example, the El Dorado Irrigation District lowered its minimum storage tank levels and installed an additional 5-million-gallon storage tank, which reduced its on-peak electricity usage by more than 60 percent (CEC 2005). Third-party DR aggregators have also begun focusing on the agricultural community, and manual DR participation has increased among growers recently.

In our interviews with experts from the agricultural sector, they indicated that, in order to improve operational flexibility on a farm, growers need the confidence to be willing to change irrigation schedules with relatively little advance notice. These assertions are similar to those made by Olsen et al., who indicate that the remaining issues still limiting the participation of agricultural customers in DR include (1) insufficient operational flexibility and (2) insufficient communication and control infrastructure (2015). Since maximizing crop yields while minimizing crop risks is the growers' primary goal, they often

see impromptu changes to irrigation as high-risk propositions. This explains why most DR in the agricultural sector is currently controlled manually; growers receive advanced notice of DR events and decide whether to manually shut off pumps and other processes. Without communication and control infrastructure in place, participation in DR involves high transaction costs, making it difficult to secure large quantities of reliable DR from the agricultural sector.

Automated demand response (ADR) is a technology and communications strategy that allows irrigation control systems to automatically and rapidly respond to DR signals from the grid, while still leaving the grower the ability to override a DR event call if they deem it necessary. Enabling an irrigation system for ADR can face resistance, however, due to the need for installing variable frequency drives (VFDs) and/or automatic pump controls, the possibility of changing growers' irrigation habits (Marks et al. 2013), and the added uncertainty that an irrigation schedule optimized for peak load shifting may harm crop health (Olsen et al. 2015). One outstanding technological gap is developing a method for estimating risk to crop using data-driven algorithms and forecasting. However, growers typically don't have access to real-time data on plant and soil moisture levels; only 12% of growers in the United States use either soil or plant moisture-sensing devices to help determine when to water crops (USDA 2013). Experts also proposed that on-farm advanced water metering could help alleviate this concern by quantifying water volumes dispensed and, through data-driven algorithms, estimating risk of crop damage. These algorithms have not yet been developed, but present an opportunity for lessening the potential risk from operational changes such as daily load shifting or fast-response DR. Demonstration projects could be instrumental in quantifying the DR potential and in providing the evidence needed to ameliorate concerns of crop risk, resulting in a substantial increase in the amount of DR potential realized in the agricultural sector.

Looking to a future electric grid with greater integration of intermittent renewable energy resources, there are likely to be large ancillary services (AS) markets to support grid reliability and efficiency. Current manual agricultural DR resources can provide peak load shedding, seen as traditional DR, but are not capable of supplying the highly controllable, rapid response resource necessary to provide AS. However, agricultural systems composed of mechanical pumps, water storage in the form of storage tanks and potentially in-soil storage, represent a highly flexible resource that could theoretically be capable of providing large quantities of AS. Further research into irrigation pumps' controllability, response time, and practicality is still necessary to quantify the market potential for providing such energy services.

In our interviews with experts, they see a generally slow rate of adoption of AMI technologies in this sector. We have heard many anecdotal explanations for this, including: concerns of losing control of an irrigation schedule; an increased risk to crops; and a

general disinterest in having water use monitored, recorded, and made available to others. However, further research is needed to better understand these barriers to adoption and the associated opportunity costs.

2.3 Supporting Energy, Water, and Climate Policy Goals

With increasing concerns about greenhouse gas emissions, water scarcity, and natural resource management, municipalities worldwide are facing stricter regulations regarding water and energy efficiency as well as pressure to provide evidence that a resource management program is achieving those goals. A number of studies have suggested that environmental goals can be met more efficiently and economically by approaching energy conservation through water usage; for example, in 2005, the CEC reported that California's state energy efficiency goals could be met by focusing solely on water use, at half the cost of traditional energy efficiency targets, as the energy savings associated with water efficiency are, on average, less expensive to achieve (CEC 2005). However, there is still considerable uncertainty about how to accurately measure the embedded energy in water, quantify cost savings, allocate energy reductions, and develop a transparent metric for joint water-energy programs (Cooley and Donnelly 2013; Young and Mackres 2013). The wealth of data generated by water and energy AMI systems could provide crucial evidence, and not only improve our understanding of water and energy consumption, but also identify areas with the greatest potential for improved strategic resource management.

2.3.1 Measurement and Verification

Measurement and verification (M&V) is commonly undertaken to quantify the benefits of an energy or water efficiency measure, and is crucial to establishing its value to facility owners, operators, customers, and utility programs. M&V involves first documenting the energy and/or water use of a facility before and after an efficiency measure is installed, then quantifying and attributing changes in usage to the measures. In the energy sector, M&V efforts can comprise 1-5% of portfolio costs (Jayaweera et al. 2013). Improved and automated M&V methods that typically rely on AMI data can generate more reliable baselines to predict what the energy use might have been if a measure was not implemented (Granderson et al. 2011). These AMI-based M&V methods can be faster and more accurate, which enables more cost effective energy efficiency programs (Granderson et al. 2015). Recent research suggests that coordinated AMI systems can reduce the uncertainty in cost and benefit valuation, allow for more transparent computations, and improve the attribution of costs and benefits (Young and Mackres 2013).

2.3.2 Program Design and Prioritization

In addition to the M&V of joint water-energy programs, water AMI data can contribute substantially to supporting the prioritization of the most effective water and energy

conservation strategies. This is highlighted in Stewart et al.'s 2010 paper, "Web-based knowledge management system: linking smart metering to the future of urban water planning". Australia faced significant sustained drought during 2002-2012, while water demand growth forecasts indicated a 37% growth between 2001 and 2031 (Birrell et al. 2005). Stewart et al. observed that, while there were numerous strategies being implemented for resource management during this severe drought, there was often inadequate data to support which solutions had the most profound or immediate impacts on water demand. Stewart et al. proposed a web-based knowledge management system to leverage the installed water metering technology to improve infrastructure planning and management, water demand management, and communication of water consumption metrics to customers. Finally, Stewart et al. argued that data from water AMI is imperative to manage the increasing stress on Australia's ever-shrinking water supply.

In the agricultural sector, irrigation districts and farms typically collect very little data about water consumption (surface or groundwater), which can be a lost opportunity for improved on-farm water management. A water AMI system that also has soil moisture sensors, for instance, could aid in linking water and energy use in ways that allow growers to optimize these resources jointly (Rivers et al. 2015; Shukla and Holt 2014). Further, the dearth of operational data about where irrigation water comes from, how and when it is applied to fields, and the energy associated with conveying water and delivering through an irrigation system leads to great uncertainties about how to best design and implement utility and regulatory programs that target energy and water savings. As a substantial knowledge gap, we recommend studies focused on collecting this information in order to conduct a reliable scoping study examining the potential costs and benefits of further work in this area. However, no pilot studies or quantitative information exists on the value of water-energy information in agriculture.

3 Challenges and Barriers

In order to achieve widespread adoption of advanced water metering and its joint utilization by both the water and energy sectors, a number of challenges and barriers need to be addressed and overcome. We identified three primary challenges and barriers to the utilization of advanced water metering to realize energy benefits: (1) how water utilities capture value from the energy services provided by water metering; (2) the impact of water rights, especially appropriation doctrine in the American West, on incentives to install water meters and share the meter data with the public, regulatory bodies, or utilities; and (3) effective coordination and cooperation between water and energy utilities.

3.1 Value Capture

Advanced water metering systems can be expensive when compared to traditional metering devices. Project costs range widely based on the number of customers, the specific metering and communications technologies selected, the level of software integration, and the state of metering system prior to AMI/AMR implementation. A survey of water AMI and AMR projects in Australia and New Zealand found project costs ranging from as low as $45,000 to simply upgrade 5,000 water meters to smart water meters; to as high as $36M to install a full AMR system for nearly 60,000 residential and non-residential meters (Beal and Flynn 2015). Additionally, Beal et al. found that, of 16 funded advanced water metering projects surveyed in Australia and New Zealand, 9 (56%) were wholly funded by the water utility and 15 (94%) were at least partially funded by the water utility, with funding partners including federal and state governments, schools, and farmers. The same study found that utilities most often identified reducing non-revenue water as their top priority, with improved demand forecasting as another popular motivation. While both of these priorities have direct ties to energy benefits, as reducing non-revenue water reduces embedded energy lost in the system and improving demand forecasting improves a water utility's ability to provide electric DR services by reducing the risk that deferring pumping will result in insufficient supply, none of these benefits were quantified by the study.

Many water districts have observed that, due to high capital costs, making the business case for water AMI is currently difficult (Zunino 2015). While pilot studies are beginning to demonstrate and quantify the associated energy benefits of water AMI, the question often remains as to how water utilities capture and fully monetize these benefits. How this question is resolved depends on state and local policies, which are often determined by state Public Utilities Commissions. For example, the California Public Utilities Commission (CPUC) is currently in the process of implementing an embedded energy cost calculator into its energy and water efficiency program evaluations. The overall lack of valuation analysis of the energy and GHG benefits of water AMI remains a significant gap in the open

literature. A more thorough understanding of the energy benefits and clearer pathways to capturing these benefits for the water utility could improve AMI's business case, and possibly spur more widespread adoption.

3.2 Water Rights

In order for advanced water metering data to be collected and utilized, regulatory, operational, and legal disincentives need to be lessened or removed entirely. A major disincentive to the collection and sharing of water data in the American West is how water rights are determined. Water rights in the American West are generally *prior-appropriation rights* (US Army Corps of Engineers and Consensus Building Institute 2012). These rights are based on four principles: (1) intent, which typically consists of the application for a permit; (2) diversion, which defines the physical location; (3) beneficial use, which defines the intended purpose of a water allocation (e.g. agriculture); and (4) priority, which is the date of the first withdrawal made under the right, with older rights having priority over newer rights. A key element of the prior-appropriation doctrine is the concept of *abandonment* or *forfeiture*, which is when all or a fraction of an allocation is either not used according to a beneficial use, or is not used at all. This means that if rights owners are found to use less than they have an allocation for, they may lose a portion of their allocation permanently. This system, paired with dated reporting laws, incentivizes rights holders to obscure, or not even report, their water use, as full disclosure could jeopardize an owner's allocation.

While water AMI is a powerful technology for managing water consumption, many rights holders are hesitant to participate in utility programs (e.g. demand response) that would disclose the details of their water consumption to public utilities or threaten profits (Dinar and Mody 2003). As a result of these legal and regulatory factors, farms that embrace advanced resource management strategies, including networked advanced water metering systems, typically install independent and internal systems that do not share water data with water districts or regulatory agencies. While these internal advanced metering systems can provide farmers with the same level of information concerning their water consumption (along with soil moisture, temperature, weather patterns, etc.), these local installations lack the two-way communication between growers and the utility or irrigation district that is common in a full AMI system. The two-way communication and data-sharing attributes of AMI enable more accurate water use tracking and M&V to support joint water-energy programs and policies in the agricultural sector. This finding is important, and should be considered when setting policies and developing programs to ensure water rights holders are not deterred from participation by risk to their water rights and allocations.

3.3 Utility Coordination and Conflicting Priorities

To achieve the most energy benefits with existing and future water AMI systems, water and energy utilities would need to collaborate on individual projects and strategic planning. However, in our discussions with experts, they communicated that coordination across water and energy entities to implement joint water-energy programs is a very complex task. A number of elements are crucial to the success of a project, including: (1) determining appropriate allocation of resources between the two entities; (2) parallel project goals that encourage cooperation; (3) streamlined communications, legal review, and inter-agency procedures; and (4) standardization of AMI data. Experts also indicated that, even within municipal utilities that provide both energy and water services, cross-department collaboration and coordination can be difficult and is relatively uncommon.

A 2013 survey by Cooley et al. found that 30% of energy and water experts surveyed described the inability to share customer data due to privacy concerns as a significant barrier to the success of water-energy programs. This inability to share data is often due to legal and bureaucratic hurdles that can prevent the success of the project, but can also be caused by the fact that utilities use different software and data management architectures. Some of these issues could be solved with more widespread standardization of AMI data.
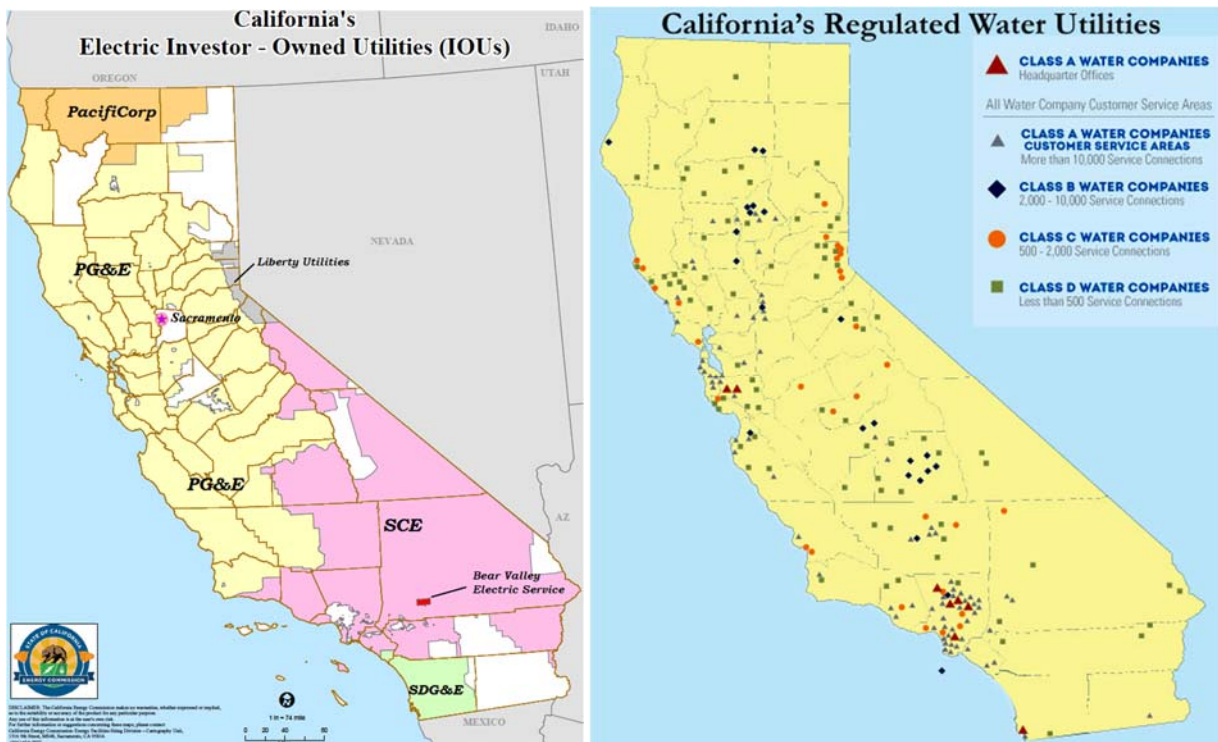
Figure 4: Left, California's Investor Owned Utilities' service territories (CEC). Right, location and size of California's regulated water utilities (California Water Association).

It is also common for significant mismatches to exist between the service territories of energy and water utilities. For example, Figure 4 shows how it is not uncommon for California's energy utilities' service territories to overlap with dozens of water utilities. This mismatch between water and energy utilities' service territories, as well as the relative number of water utilities within a single energy utility's service territory, has been cited as a slight-to-moderate barrier to improved water-energy program coordination (Cooley and Donnelly 2013).

4 Case Study: California

4.1 Background

The state of California is a leader in the collection of energy use data, with over 12 million smart meters installed across the state (IEI 2014). However, the deployment of advanced water meters and water AMI integration in California lags behind that of energy AMI, mainly due to operational needs that only energy utilities face, such as the need to accurately meter distributed energy resources and the need to enable TOU-based electricity prices. In 2004, California's Legislature passed Assembly Bill (AB) 2572, which requires all municipal water connections to be metered and capable of enabling volumetric billing for customers by 2025 (California State Assembly 2004). In effect, the resolution will increase the metering of water use statewide. Although this is a promising step, the resolution does not mandate the performance requirements of the metering or communications infrastructure. This means the deployment of advanced water meters and AMI is dependent on utility investment capabilities, incentives, and priorities. Additionally, California recently passed Senate Bill 555, which: (1) requires urban retail water suppliers to complete and submit a water loss audit report annually beginning in late 2017; and (2) dictates that the State Legislature to adopt rules regarding the standardization of these audits by January 1, 2017 (California State Senate 2015). It remains unclear exactly how these Bills will impact the state of advanced water metering in California. However, California is one of the few states that has investigated and taken steps to better quantify the embedded energy of water consumption and the energy demands of the water system as a whole.

4.2 Embedded Energy of Water in California

How weather variation and long-term climate change impact the water-related energy needs of the municipal, industrial, and agricultural sectors are not well understood, though there are assumed to be significant differences as California's surface water availability decreases, groundwater depths increase, and severe drought continues to impact the state. To determine the scale of the opportunities for improving resource use in California, the CEC, Maupin et al., and the California Department of Water Resources (CDWR) performed assessments of water and water-related energy use in California. The agricultural, industrial, and municipal sectors' estimated annual water consumption and water-related energy consumption are shown in Table 4. It is important to note that the values in Table 4 are not for identical calendar years, however; though these studies represent some of the most comprehensive assessments currently available for California, data collection in this field is infrequent and uncoordinated, which has posed another analytical challenge.

Table 4 shows that the agricultural sector is the largest consumer of water, accounting for 75% of all water consumed in the state; municipal use accounts for approximately 24%, and industry the remaining 1%. Table 4 also shows that the municipal sector uses the most water-related energy, at 64%, agriculture uses an additional 22%, and industrial uses the remaining 14%. The last column in Table 4 is an estimate of each sector's energy intensity of water, or embedded energy, calculated from the two other columns according to Equation 2. This calculation, shown in the Water-Related Energy column, is consistent with this report's definition of embedded energy, which does not include end-use associated energy.

Equation 2 $$Embedded\ Energy\ (^{kWh}/_{MG}) = \frac{Energy\ Consumption\ (kWh\ per\ year)}{Water\ Consumption\ (MG\ per\ year)}$$

Table 4: Water and Energy Consumption by Sector in California

Sector	Water-Related Energy Consumption (GWh/year)	Water Consumption (BG/year)	Embedded Energy of Water (kWh/MG)
Agriculture	10,560[1]	8,500[2]	1240
Industry	~6800[1]	160[3]	42,500
Municipal	~30,600[1]	2,700[3]	11,300
1 (CEC 2005); 2 (Maupin et al. 2014); 3 (CDWR 2013); Shading indicates magnitude of value, darker = larger.			

Despite using the least water and water-related energy of the sectors, the industrial sector has the highest embedded energy, at 42,500 kWh/MG. This result is not surprising, as industrial processes often pressurize, heat, and/or treat water, all of which are energy intensive. Additionally, industries that reuse water will have drastically larger energy intensities, as the same volume of water may be put through a process multiple times. Municipal water use is the next most energy intensive, at 11,300 kWh/MG. Agricultural water use is the least energy intensive, at approximately 1240 kWh/MG, however these values can be highly variable as the energy use is attributable to many factors such as geographic location, climate, and water source. For example, in their 2003 report, Burt et al. indicate that the embedded energy of agricultural water in the coastal regions of the state is approximately four times that of water in the Central Valley, owing in part to the energy cost of conveying water to the coast.

For comparison, Table 5 shows bottom-up estimates of the energy intensity ranges for a number of segments of the water cycle. Water treatment has the largest range of energy

intensity, with the low end representing agricultural or industrial water that does not need to be potable and the high end representing desalinated water treatment. Water supply and conveyance have the second largest range of energy intensity, with the low end representing gravity-fed supply systems for which no pumping is necessary and the high end representing large inter-basin transfer projects such as the State Water Project (SWP).

Table 5: Range of Energy Intensities Water Use Cycle Segment (CEC 2005)

Water-Use Cycle Segments	Range of Energy Intensity (kWh/MG)	
	Low	High
Water Supply and Conveyance	0	14,000
Water Treatment	100	16,000
Water Distribution	700	1,200
Wastewater Collection and Treatment	1,100	4,600
Wastewater Discharge	0	400
Recycled Water Treatment and Distribution	400	1,200

The one major water-use cycle segment not included in Table 5 is the end-use itself. For example, the energy intensity of heating water for residential clothes washing or pressurizing industrial water is not included in Table 5. These end-use-related energy intensity factors can be a significant fraction of the overall energy intensity of water, especially in the industrial sector.
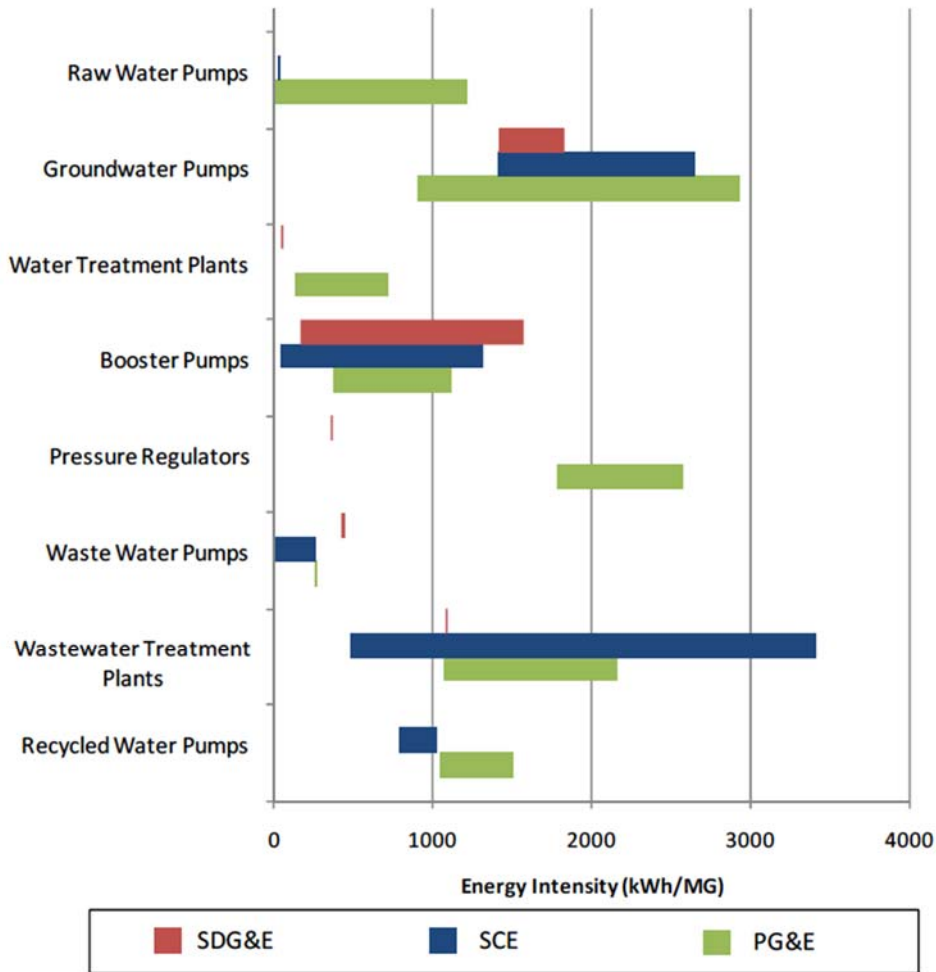
Figure 5: Energy intensity range by component for California's three IOUs (GEI Consultants and Navigant Consulting 2010).

Figure 5, reproduced from the 2010 report, "Embedded Energy in Water Studies Study 2: Water Agency and Function Component Study and Embedded Energy-Water Load Profiles", shows the ranges in energy intensity of various components of the water cycle for California's three Investor Owned Utilities (IOUs). While these values are not from a representative statistical sample, they are useful for scoping and understanding variability and embedded energy savings opportunities.

The values from Table 4, Table 5, and Figure 5 will be used to scope the possible energy impacts of AMI across California.

4.3   Potential for Energy Efficiency

The information and controls provided by AMI to customers and utilities can have large energy efficiency impacts. Such opportunities include more efficient system operational

strategies, energy savings through water conservation and leak detection, and changes in consumer behavior. The following subsections discuss the scale of these opportunities in the municipal and agricultural sectors in California.

4.3.1   The Municipal Sector

DeOreo et al. found that customer-side leaks waste 31 gallons of water per household per day in California residences, which is approximately 17% of all indoor consumption (2011). An EBMUD pilot study that installed AMI and utilized an online customer portal where customers could examine their hourly water use observed subsequent water conservation between 5% and 50%, with an overall average of approximately 15% after installation (EBMUD 2014). Given that 2.9 trillion gallons of water are consumed in the urban sector annually in California (CDWR 2013), and assuming a conservative 10% savings from behavioral and customer-side leak fixes, implementing water AMI statewide could reduce statewide water consumption by 290 billion gallons annually. Using the embedded energy estimates from Table 4, these water savings could result in approximately 3.3 TWh of embedded energy savings[1] through consumer behavior change and customer-side of the meter leak fixes alone.

Regarding utility-side leaks, a report prepared for Southern California Edison calculated that the physical losses in California's water distribution infrastructure account for approximately 11% of the urban water consumed in the state (Water Systems Optimization 2009). The authors further estimated that 40% of these losses are recoverable economically, assuming the lost water is valued at retail prices, while noting that value to be "reasonable and rather conservative." This assumption is based on the standard practice of "reactive management," which means fixing leaks when they are reported to the utility by customers or the general public. If AMI technologies could reduce the cost of recovering these losses through rapid, automated leak identification and preemptive pipe replacement (replacing water mains before they burst), we suggest 75% of these real losses may be economically recoverable. This would imply 8% of urban water consumed in the state, equivalent to 230 BG/year, could be conserved with AMI. Using the estimates of embedded energy from Table 4, these water savings could result in approximately 2.6 TWh of embedded energy savings[2] through avoided production, treatment, and distribution of water.

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[1] 3.3 TWh was calculated by multiplying 290 BG/year by the municipal embedded energy value, 11,300 kWh/MG, found in Table 4.
[2] 2.6 TWh was calculated by multiplying 230 BG/year by the municipal embedded energy value, 11,300 kWh/MG, found in Table 4.

Together, utility-side and customer-side leak repair could have significant energy-saving potential in the municipal sector. The important outstanding question is how, if at all, water utilities can capture the value of these energy savings as an added incentive for upgrading and installing water AMI systems. The CPUC's new Water Energy Cost Effectiveness Calculator aims to give utilities proper credit for energy savings attributable to water efficiency programs (CPUC 2016), however we are unaware of a demonstrated project where behavioral or AMI-driven water savings were given credit for embedded energy savings.

4.3.2   The Agricultural Sector

A recent study reports that more than 10 TWh of electricity is consumed annually for pumping agricultural irrigation water in California (Marks et al. 2013). Researchers have found that improved data collection of both water and energy use on farms is crucial to improving irrigation energy efficiency, especially when integrated with on-farm energy management systems (Rocamora et al. 2013). A case study of a pressurized irrigation pumping system found that basic electrical and hydraulic measurements at the pumping station could achieve more optimal pump operation, resulting in energy savings of up to 14% (Moreno et al. 2007). Applying a conservative estimate of a 10% energy efficiency savings from implementation of on-farm AMI and improved control strategies for the 10 TWh of water-related energy use, the agricultural sector could certainly realize 1 TWh of savings annually.

On-farm leaks waste both water and energy, but can also present a threat to crop health, as undetected leaks can saturate and kill water-sensitive crops. While there are some companies (e.g. PowWow Energy) marketing leak detection algorithms to the agricultural sector, there is no data or well-supported estimates available for the magnitude of on-farm leaks. California's Sustainable Groundwater Management Act, which came into effect in 2016, gives water agencies the mandate to develop sustainable water management strategies, including enhanced data collection on groundwater withdrawals and water losses due to leaks (State of California). While it is still unclear how most agencies will choose to develop and implement their plans, we recommend they explore the potential of AMI systems to address sustainable water-energy management at both the customer- and agency-level.

4.4   Potential for Peak Load Reduction

Peak electric load hours are typically in warm summer months and occur during the mid to late afternoon. These peak demand hours require electric utility companies to procure expensive generation portfolios capable of supplying power during these hours. Demand response and permanent load shifting are two solutions to this issue. The California Energy

Commission has funded a number of studies examining the peak electricity demand impacts of water. In the seminal 2005 report, *California's Water – Energy Relationship*, the CEC estimated that peak electrical demand could be reduced by approximately 250 MW if "water agencies statewide viewed their [water] storage as an energy asset as well as a water asset." For context, as of 2014, there was approximately 2000 MW of DR in California (Jarred 2014). Additionally, it was estimated that California's water-supply related demand exceeds 2000 MW (House 2007). We suggest that further peak load reductions and load shifting through DR could be enabled by more widespread AMI and improved co-optimized water-energy modeling. We discuss this potential for the municipal and agricultural sectors in the following subsections.

4.4.1   The Municipal Sector

In a 2007 follow-on study to the CEC's *California's Water – Energy Relationship* report, House et al. found that 500 MW of water agency electrical demand is used to provide water and sewer services to residential water customers throughout California. This estimate does not include the demand needed to supply water to other urban customers, including commercial and industrial customers. These findings show that a significant amount of peak load is present that, with proper infrastructure investment (e.g. water storage and AMI) and improved operations, could be partially shifted to off-peak hours.

Unfortunately, there is very little quantitative information about the specific operational changes that AMI enables in the municipal sector. In our interviews with them, experts indicated that the data provided by AMI would enable more flexible and reliable operation of water systems. Additionally, water AMI systems that measure hourly customer consumption would allow water utilities to use TOU water pricing tariffs to encourage off-peak water consumption.

4.4.2   The Agricultural Sector

In a 2007 report for the CEC, House et al. estimated that roughly 60% of the state's water-related peak electrical demand is attributable to pumping agricultural irrigation water. Further research has examined the shape of agricultural load profiles over both daily and seasonal timescales. From a recent report by Olsen et al., Figure 6 shows the daily average demand profile for approximately 35,000 agricultural customers from Pacific Gas and Electric's service territory for the years 2003-2012. It shows that the percent of energy used during peak hours (between 12 and 6 PM), increased from 2003 until 2006, when peak demand was 120% of the annual average, and has since decreased, with peak demand at approximately 105% of annual average demand in 2012. This shows that, while the current trend is moving towards reducing the intra-day variation in hourly load, there is still a large amount of irrigation occurring during peak hours.

California currently has approximately 65 MW of agricultural peak-shedding DR capabilities, which represents approximately 6.5% of the 1 GW of estimated load shed potential in the state (Olsen et al. 2015). This DR is mostly manually operated, and is eligible for the energy market and, more importantly, capacity credit, which is currently the principle value stream for peak-shaving DR. A recent interim report from LBNL's 2015 California Demand Response Potential Study found 68 MW of agricultural peak-shedding DR capabilities to be cost effective by 2025 (Alstone et al. 2016). However, this initial study did not explore changes to the underlying technology strategies employed in the agricultural sector, and relied on past customer enrollment rates to estimate the fraction of growers participating in DR, which might be significantly impacted by a rollout of advanced water metering systems.
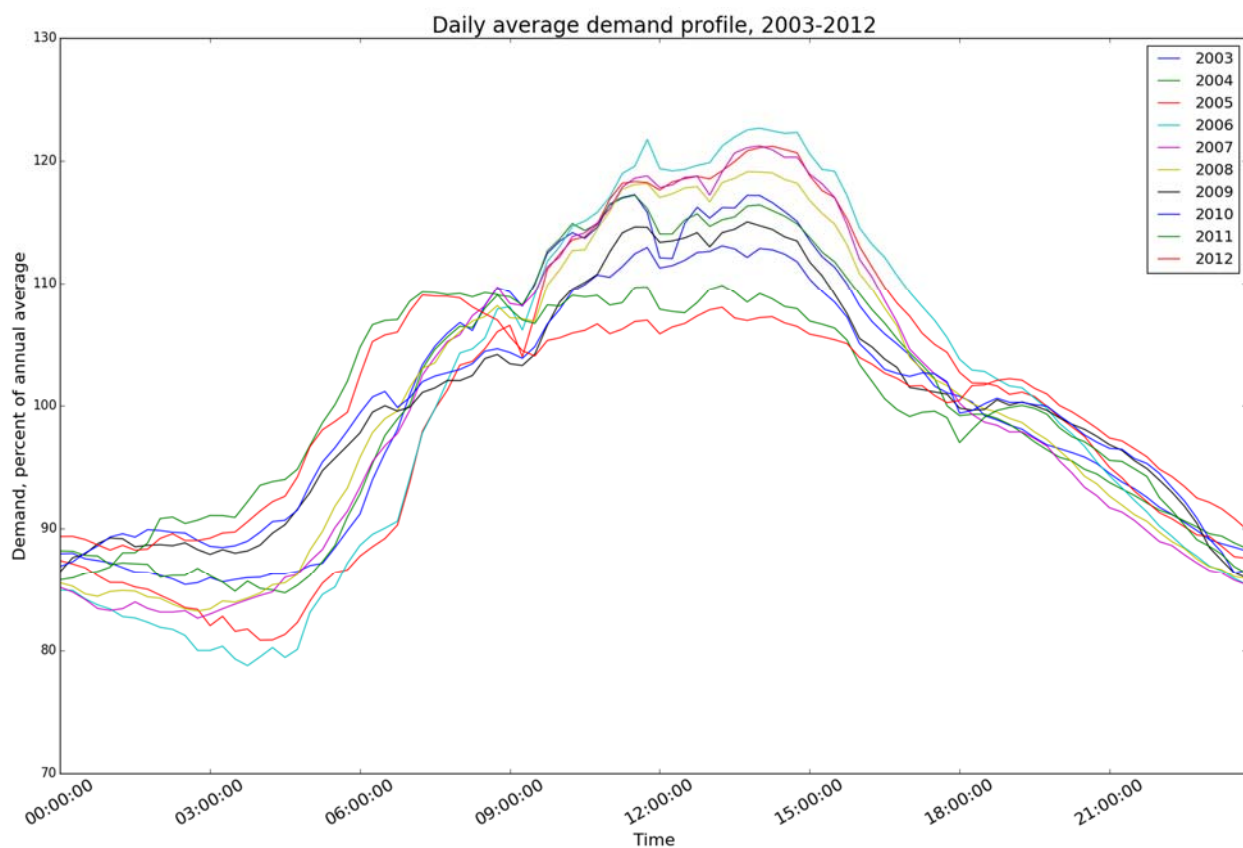
Figure 6: Average daily demand profiles for approximately 35,000 agricultural customers' interval meters from PG&E's service territory, 2003-2012. Figure shows how daily agricultural load profiles have flattened since 2006, but still peak during mid-day hours. Reproduced from Olsen et al. (2015).

An additional area of interest for future research and demonstration projects is that of agricultural loads providing AS, which include grid products such as frequency regulation and contingency reserves. California's ambitious Renewables Portfolio Standard mandates that 33% of the electricity used in the state come from renewable energy sources by 2020. As renewables are more difficult to forecast, have high variability, and cannot be controlled

in the same way as traditional generators, it is predicted that the demand for AS will grow with higher renewable penetration. Figure 6 suggests that, since agricultural loads are present at all times of day, they could be available to meet AS needs at the most opportune times of day, such as during multi-hour evening ramps. We recommend further scoping analysis for this potential opportunity to meet the future grid needs in California, as well as other states and countries with ambitious renewable energy goals and sizeable agricultural sectors. As co-authors on the Alstone et al. *Demand Response Potential Study*, we are aware of ongoing work that will explore and quantify the value of agricultural DR resources to AS markets and, more generally, grid operations in California.

4.5   Summary

Table 6 summarizes the water and energy impact potential for a number of high-level analyses discussed earlier in Section 4. We do not believe this to be an exhaustive list of the opportunities for advanced water metering to have associated energy benefits, however in many cases data does not exist to make even high-level estimates of potential. We recognize that other opportunities exist, including:

- Enabling increased DR participation from municipal water utilities and agricultural customers through improved water forecasting and management and reduced risk.
- Leak detection and repair in the agricultural sector.
- Improved pressure monitoring and management in municipal water systems.

Table 6: Summary of estimated water and energy impact potential for various water-related advanced metering strategies in California.

Advanced Metering Strategy	Water Savings Potential	Energy Impact Potential
Water AMI for Municipal Customer-side Leak Detection	290 BG/year	3.3 TWh of embedded energy savings
Water AMI for Municipal Utility-side Leak Detection	230 BG/year	2.6 TWh of embedded energy savings
On-Farm Water-Energy Metering for Pump Operation Optimization	N/A	1 TWh of energy efficiency savings
Energy-Centric Operation of Existing Water Storage	N/A	250 MW of peak DR

5   Concluding Remarks

This report is a first attempt at compiling and documenting the various opportunities for advanced water metering technologies, including AMI, to provide energy benefits. The market for such technologies is expanding, and the sensing and network communications technologies are improving. Our broad finding in reviewing the energy landscape for water AMI is that these technological advances are largely valued for purposes of improved water management or conservation. Apart from electricity demand response programs, we found very little discussion or consideration of the direct benefits to the energy sector from water AMI. This is an important gap in measuring the benefits of water AMI, as an emerging technology, to meet the electrical needs for present and future grid needs.

Through a review of the open literature and interviews with nine experts from the water and energy sectors, we document how data provided by advanced water metering systems has the potential to realize energy efficiencies and provide energy services to the grid. Currently, stakeholders consistently agree that the dearth of water and water-related energy-use data hinders efforts in the water-energy nexus, and that water AMI systems could have far-reaching co-benefits with the energy sector, policy, program design, customer education, and overall resource efficiency.

The two sectors of most interest to us were the municipal and agricultural sectors. In the municipal sector, opportunities include more rapid and accurate leak detection on both sides of the meter, improved infrastructure design, and more efficient system operation. In the agricultural sector, opportunities include improved water and energy efficient irrigation, crop risk quantification, and a highly flexible demand response resource for both peak load shedding and ancillary services. We also discuss how advanced water metering may help overcome barriers to improved water-energy policy, joint water-energy utility program design, and more efficient resource use by consumers.

A limitation of this report is the lack of available information for quantifying the realized energy and energy-related monetary benefits of water AMI. As a result, the findings discussed in the report are often anecdotal owing to the absence of this information. A continuation of this work is to quantify, analyze, and prioritize the potential benefits of water AMI in individual sectors through deeper, data-driven studies.

6 Future Work

Through our review of the open literature and interviews with water-energy experts, we confirmed that there is very little data about the interconnection of water and energy systems. This lack of data makes assessing the energy benefits of advanced water metering difficult, and therefore impairs their prioritization compared to other emerging energy technologies. This report documents the anecdotal evidence that water AMI has the potential to address future grid needs and improve the energy efficiency of the water system. However, the anecdotal evidence, and limited quantitative information, is insufficient to develop actionable policies, technology adoption goals, incentive programs, or grid integration strategies. We recommend and support further data gathering efforts. As follow-on work to this scoping study, we see the need for data gathering and deeper analysis of the opportunities presented in this report. In addition to data gathering efforts, future research in this area should focus on the following key issues:

- What are the performance requirements of water AMI to meet specific grid needs? For example, describe the technologies and infrastructure requirements necessary to support automated DR for ancillary services in the agricultural sector.
- What data and associated analytical techniques are necessary to confirm and analyze the benefits of water AMI projects? The measurement and verification of benefits is crucial for utilities, the DOE, and others to justify supporting investments in them.
- What characteristics of water AMI systems are crucial to realizing the energy benefits identified in this report? For example:
  - How important is water flow meter precision, and what level of precision is sufficient to still be cost-effective?
  - What sensors, analytics, and controls are necessary to sufficiently quantify and forecast crop risks that could attract greater farmer participation in ADR?
- A cost survey of water AMI projects detailing the costs and capabilities of AMI systems as well as exploring how costs scale with utility service territory and/or number of customers, and how they differ across sectors.
- Case studies of current and past advanced metering projects that identify value pathways for water meter data to realize energy benefits and have made efforts to monetize them.
- What regulatory opportunities exist for policy makers to encourage water AMI, especially to realize energy benefits?

- What are the best practices for implementing and operating water AMI systems, and how do they differ if energy services (such as DR) are incorporated?

The above matters are perhaps best explored through case studies across different regions and sectors, in order to develop order-of-magnitude estimates of market benefits.

We also suggest the development and design of a publicly-available tool for policy makers, utilities, businesses, homeowners, and researchers to estimate the embedded energy in their water based on parameters, including but not limited to, end use, location, time of day, season, and elevation. The California Public Utilities Commission recently produced a version of such a tool for California, with the goal of increasing value capture for water and energy utilities, as well as incentivizing program cooperation (CPUC 2016). Such a tool would be useful for other regions of the U.S., particularly those that face water scarcity and water valuation challenges. A valuable data gathering and analysis task that remains is a nationwide study of the embedded energy of water across the agricultural and urban sectors. National level databases such as this would be powerful assets for improving regional resource management and furthering research in the water-energy nexus.

Finally, demonstration projects focused on the feasibility and cost of integrating water AMI systems explicitly for energy benefits are needed. These could include projects to demonstrate how water AMI data enables electric DR participation, how in-home displays can be best implemented to realize joint water-energy benefits, or what the cost-optimal distribution of flow meters, as well as level of precision, is for detecting before-the-meter leaks.

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