Energy Research and Development Division
FINAL PROJECT REPORT

REDUCING WASTE IN RESIDENTIAL HOT WATER DISTRIBUTION SYSTEMS

National Lab Buildings Energy Efficiency Research Projects

Prepared for: California Energy Commission
Prepared by: Lawrence Berkeley National Laboratory

JUNE 2014
CEC-500-2015-004

PREPARED BY:

Primary Authors:
Jim Lutz
Steven Lanzisera
Anna Liao
Christian Fitting
Chris Stiles
Margarita Kloss

Lawrence Berkeley National Laboratory
1 Cyclotron Road, MS 90R2000
Berkeley, CA 94720
Phone: 510-486-4762 | Fax: 510-486-4673

Contract Number: 500-10-052

Prepared for:

California Energy Commission

Brad Meister
Project Manager

Heather Bird
Contract Manager

Virginia Lew
Office Manager
Energy Efficiency Research Office

Laurie ten Hope
Deputy Director
ENERGY RESEARCH AND DEVELOPMENT DIVISION

Robert P. Oglesby
Executive Director

LEGAL NOTICE

DISCLAIMER

ACKNOWLEDGEMENTS

This work was supported by the California Energy Commission, Public Interest Energy Research Program, under Agreement No. 500-10-052.

The project team at Lawrence Berkeley National Laboratory would like to thank the sponsor, the Public Interest Energy Research Program of the California Energy Commission, Heather Bird, Chris Scruton, and especially the Project Manager, Brad Meister.

The project team extends a special thanks to the people who volunteered their houses for this study.

Thanks to the many industry professionals and individuals who shared their ideas and feedback and contributed to this project.

Thanks to Lawrence Berkeley National Laboratory (LBNL) staff support, including Paula Ashley. Thanks, also, to our reviewers for their generosity and time improving this report.

This work was supported by the California Energy Commission's Public Interest Energy Research Program and by the Assistant Secretary for Energy Efficiency and Renewable Energy, Building Technologies Program, of the U.S. Department of Energy under Contract No. DEAC02-05CH11231.

PREFACE

The California Energy Commission Energy Research and Development Division supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

The Energy Research and Development Division conducts public interest research, development, and demonstration (RD&D) projects to benefit California.

The Energy Research and Development Division strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Energy Research and Development Division funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy Innovations Small Grants
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Reducing Waste in Residential Hot Water Distribution Systems is the final report for the *National Lab Buildings Energy Efficiency Research Projects* (contract number 500-10-052, conducted by Lawrence Berkeley National Laboratory. The information from this project contributes to Energy Research and Development Division's Buildings End-Use Energy Efficiency Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

This research project investigated water and energy use in hot water distribution systems in existing California homes. A hot water distribution system delivers hot water from the water heater to the end uses, such as showers and sinks. Heating water accounts for approximately 40 percent of California's residential natural gas consumption. Increasing the efficiency of the hot water distribution systems in California houses would reduce this significant natural gas load. Benefits to ratepayers will accrue from improved hot water distribution system designs for new homes and major retrofits to existing homes. The findings can be used to initiate upgrade of existing plumbing and building energy efficiency codes.

Lawrence Berkeley National Laboratory developed a wireless sensor network technology to measure water temperature and flow rate at indoor end uses and the water heater. Monitoring systems were installed in 21 homes from July 2013 to February 2014. A total of 5–21 end uses were metered in each house. Water temperatures and flow rates were recorded once per second whenever water was flowing. Water flow and temperature data were successfully collected and uploaded to a data server.

This research suggests that the efficiency of hot water distribution systems in California homes can be disturbingly low. Preliminary analysis demonstrates that for some shower, kitchen sink, and dishwasher events, only half of the hot water energy provided by the water heater are actually being delivered at the end use. This supports the opportunity to improve the design of hot water distribution systems. Further analysis of the impact of the hot water distribution system could be used to guide the revisions to the plumbing codes and the building energy efficiency codes.

Keywords: energy efficiency, hot water, hot water distribution systems, wireless sensor, water efficiency

Please use the following citation for this report:

Lutz, Jim; Steven Lanzisera; Anna Liao; Christian Fitting; Chris Stiles; Margarita Kloss. (Lawrence Berkeley National Laboratory). 2014. ***Reducing Waste in Residential Hot Water Distribution Systems.*** California Energy Commission. Publication number: CEC-500-2015-004.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

Introduction

Heating water accounts for approximately 40 percent of California's residential natural gas consumption. Hot water end uses in homes are primarily showers, faucets, dishwashers, and washing machines. Increasing the efficiency of the hot water distribution systems in California houses would reduce this significant natural gas load. In houses, the hot water distribution system delivers hot water from the water heater to the end uses, such as showers and sinks. Measuring the efficiency of hot water distribution systems is difficult and has only been done a limited number of times. Previous work suggests that efficiencies for specific end uses may be surprisingly low. This project investigated hot water distribution system efficiency in California homes.

Project Purpose

This project evaluated indoor water use in 25 California homes for six months. The temperature and flow rates of indoor hot and cold water use were measured at the end-use points and at the water heater in each house. These measurements were then used to calculate the waste of water and energy caused by the hot water distribution systems. This work indicates the potential for energy and water savings from improvements to hot water distribution systems in California's housing sector.

Stakeholder involvement included feedback during an Energy Commission Residential Water Heating Program Project Advisory Committee Meeting, input from plumbers, and presentations of interim results at the American Council for an Energy-Efficient Economy, Hot Water Forum and Summer Study.

Project Process and Results

Lawrence Berkeley National Laboratory developed a wireless sensor network technology to measure water temperature and flow rate at indoor end uses and the water heater. The wireless sensor network consists of sensor units, each containing a flow meter and thermistor, connected to wireless motes transmitting data to a central "manager" mote, which in turn posts data to a server at Lawrence Berkeley National Laboratory via the Internet. Water temperatures and flow rates are recorded once per second whenever water is flowing.

The hot water distribution system monitoring systems were installed in 25 homes from July 2013 to February 2014. A total of 5–21 end uses were metered in each house. The field work yielded as much as eight months of data per house. Water flow and temperature data were successfully collected and uploaded to a data server. Depending on when a house was constructed, there can be significant differences in hot water use patterns. For example, only 32 percent of homes built before 1949 use the dishwasher at least once a week, while 70 percent of homes built from 2000–2009 will run at least once a week.

The energy efficiency of the hot water distribution systems for a hot water event is based on the energy content of the water at the fixture during the actual use divided by the energy content of all the water leaving the water heater for the event.

For a shower, the segment of stable temperature and water flow was assumed to be the useful portion of the shower. All the water used before the shower segment started was wasted. And the energy that had heated the hot water used before that time was also wasted. The energy efficiency of the hot water distribution system during a sample shower event was determined to be 53.8 percent.

While cleaning one load of dishes, dishwashers use multiple short draws of hot water. For the set of draws for one dishwasher cycle, the temperature did not consistently reach a high temperature before the draw's end. The delivered energy efficiency of the hot water distribution system for this dishwasher cycle is 47.4 percent - indicating that plumbing hot water to this dishwasher is very inefficient. The dishwasher draws are so short; it does not receive hot water until the end of the last draw in each set. This requires the dishwasher to provide its own water heating at the end use.

At the kitchen sink, the delivered energy efficiency of the hot water distribution system for this set of kitchen sink events was 52.3 percent.

Conclusions and Recommendations

Preliminary analysis demonstrates that for some shower, dishwasher, and kitchen sink events only half of the hot water energy inserted into the hot water distribution system at the water heater is actually being delivered at the end use. This supports that there is an opportunity to improve hot water distribution system design.

This research suggests that the efficiency of hot water distribution systems in California homes can be near or less than 50 percent and further analysis of the impact of the hot water distribution systems should be used to guide the revisions for the plumbing and building energy efficiency codes.

Project Benefits

Ratepayers could benefit from improved hot water distribution system designs for new homes and major retrofits to existing homes based on these research findings. The plumbing and building energy efficiency codes could be upgraded to reflect these findings as well.

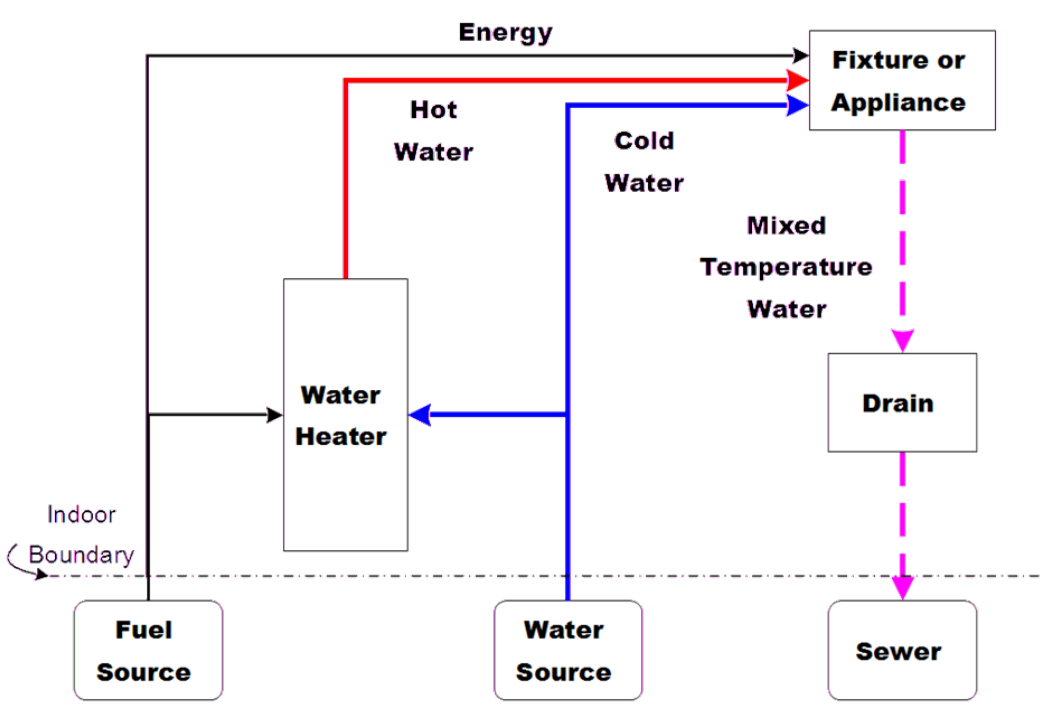
CHAPTER 1:
Project Overview

1.1 Introduction and Background

Heating water accounts for approximately 49 percent of California's residential natural gas consumption (KEMA 2010). Current residential hot water distribution systems (HWDS) often require users to run the water for some time to achieve the desired temperature, wasting energy and water in the process. What is the energy and water efficiency from water heater to end use (shower, faucet, dishwasher, washing machine)? This project's data collection system and field study were designed to answer this question and provide specific data on hot water end uses and HWDS efficiency.

Figure 1 shows a schematic view of a typical hot water distribution system in a single-family residence. The red line labeled "Hot Water" depicts the distribution system that conveys hot water from the water heater to each end use. Hot water end uses in homes are primarily showers, faucets, dishwashers, and washing machines.

Figure 1: Schematic of a Typical Hot Water Distribution System



Accurate measurements of hot water end use over a long time frame would help to guide energy efficiency standards and policy. Advances in wireless sensor network technology and software for streaming data to a remote server provide an efficient and low-cost system for a long-term field study on hot water use. The project team installed HWDS monitoring systems in 21 homes from July 2013 to February 2014. The field work yielded as much as eight months of data at each house. Depending on when a house was constructed, there can be significant differences in hot water use patterns, as supported by the U.S. Department of Energy (DOE) 2009 Residential Energy Consumption Survey (RECS 2009). For example, only 32 percent of homes built before 1949 use the dishwasher at least once a week, while 70 percent of homes built from 2000–2009 do.

1.2 Objective

This task was to improve the efficiency of hot water distribution systems in California and evaluate waste of water and energy in indoor water use in 25 California homes for six months. Field researchers installed a monitoring system consisting of a collection of wireless submeters to measure the temperature and flow rates of indoor water use, both hot and cold, at the end use points and at the water heater in each house. These measurements were then used to calculate the waste of water and energy attributable to the HWDS. This work prefigures the potential for energy and water savings from improvements to hot water distribution systems in California's housing sector.

This document is the last deliverable for Task 2.7, Reducing Waste in Residential Hot Water Distribution Systems. The research conducted in this task comprises one element of the National Lab Buildings Energy Efficiency Research Projects, California Energy Commission Award No. 500-10-052. This report describes four key elements: the field study plan; design and production of the wireless sensor network architectures; deployment of the wireless sensor networks; and data collection and analysis.

CHAPTER 2:
Field Study Plan

This field study plan describes the process for enrolling the houses in the research project. It also describes the development, calibration, and installation of the wireless sensor networks and data analysis methodologies that were used in this study.

Recruitment and selection of study participants was coordinated in accordance with the human subject protocols of Lawrence Berkeley National Laboratory (LBNL). The recruitment took place concurrently with the design and development work. A recruitment flyer explained the project to potential recruits. Interested participants were referred to a website, which included a web survey. The web survey was used to screen potential study sites and assure as wide a diversity of building types and occupants as possible. In the field study a range of housing types (single family, townhouse, condo, multi-level, foundation type); water heater types; number and range of residents; home size; and number of sinks, toilets, showers, dishwashers, and clothes washers were included.

Deployment began after the development of the wireless sensor network (WSN) was complete and the first access agreement was obtained. Deployment continued until February 2014 as access agreements were obtained and scheduling arrangements made. Ongoing debugging services were provided to the network and the homeowner to assure as complete data collection as possible at each house. The final part of the deployment phase was decommissioning at the end of the data collection period.

CHAPTER 3:
Wireless Sensor Network Architecture

The second subtask was to design the wireless sensor network. This subtask was informed by previous LBNL work on WSNs, including a pilot-phase study on hot water distribution system done for the California Department of Water Resources (Lutz, Biermayer, and King 2009) and miscellaneous electrical end-use loads (Lanzisera et al 2013). The design of the WSN was also influenced by available sensors and housings as determined in the development stage. Design of the network covered the data collection, aggregation, and analysis methodology.

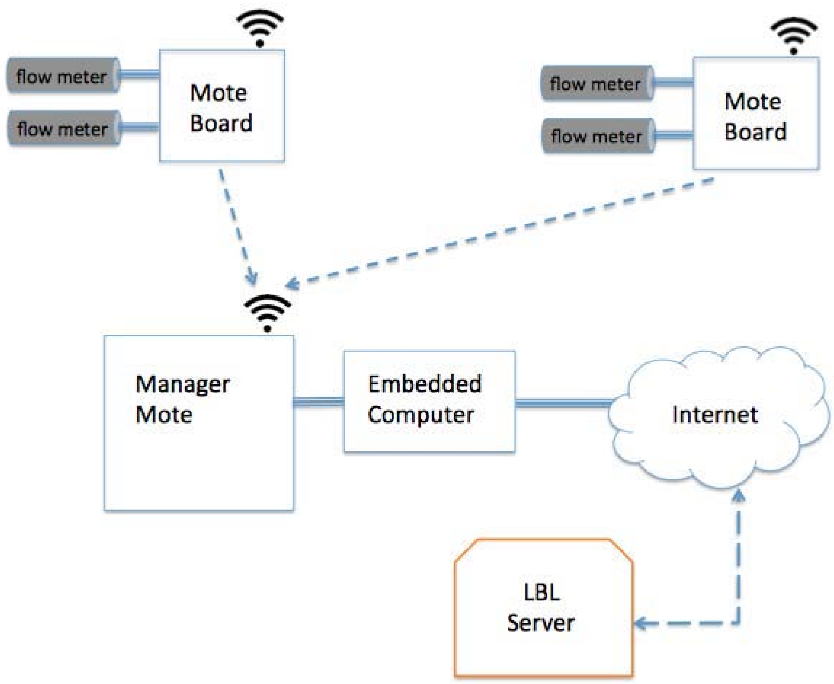
While the specifications for the WSN were being completed, development of prototype units was begun. The characteristics of low-cost sensors and housings affected the specifications for the WSN. Design and programming began after the WSN specifications were complete. Included in the development phase was the debugging, commissioning and calibration of the sensors and the wireless network components. This was done at LBNL prior to deploying the units to the field houses. A crucial aspect of development was a shakedown installation at two test houses to ensure that all aspects of the network and data collection system were working as intended.

More detailed specifications are contained in the Initial Prototype Wireless Sensor Network Specifications memo completed at the end of the design and development process. (Lanzisera and Lutz 2012).

CHAPTER 4: Wireless Sensor Network Deployment

The wireless sensor network consisted of sensor units, which each contain a flow meter and thermistor, connected to wireless motes transmitting data to a central "manager" mote. The manager mote posted data to a server at LBNL via the Internet. Figure 2 shows a schematic of the wireless sensor network.

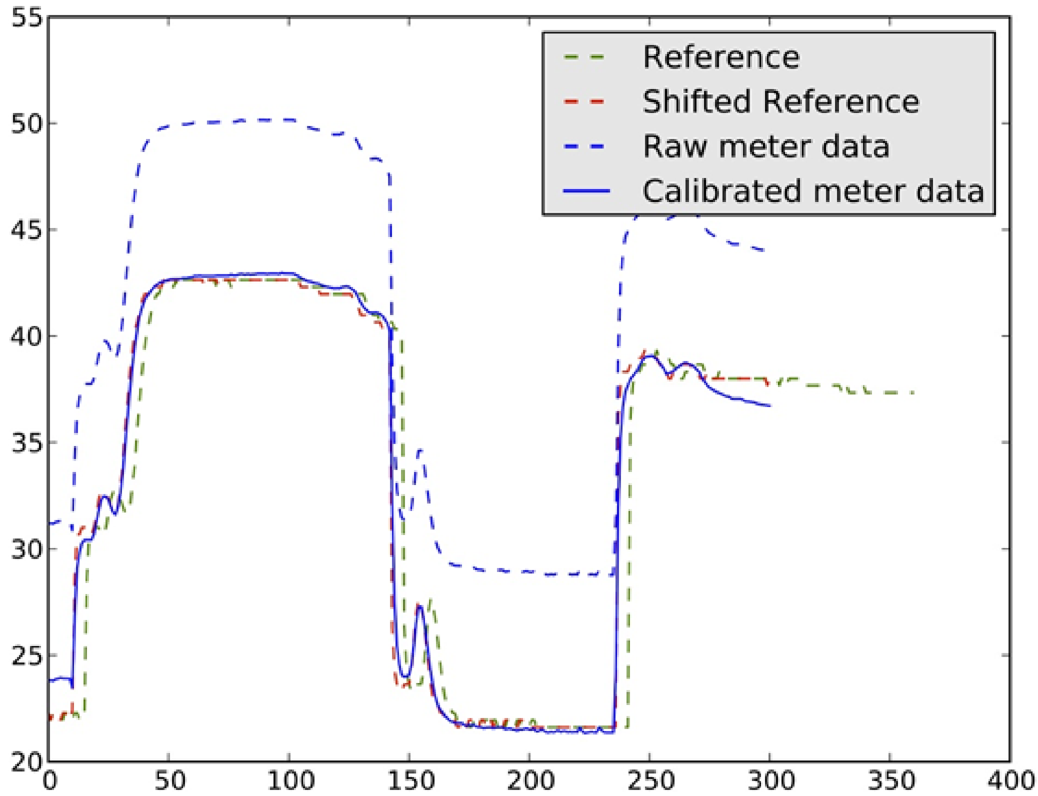
Figure 2: Schematic of Wireless Sensor Network



Initial laboratory testing measured the accuracy of the temperature and flow rate measurements of the first sensor units. The flow rates were accurate for all the sensor units tested initially. No additional measurement was needed to calibrate the flow rate reported by the flow meters. The temperature data from testing the first sensor units indicated that the measurements were not sufficiently accurate to use without correction. All the sensor units were tested with hot water in the laboratory before being installed the field. The temperatures recorded by the sensor units were corrected to match the temperatures measured by the reference equipment during the laboratory testing for each sensor unit.

The temperature calibration process consisted of two steps. The first step accounted for the unsynchronized clock in the reference temperature data logger. The raw meter data was shifted relative to the reference data to find the time shift where the shape of the temperature data from the thermistor optimally matched the reference temperature data logger. The second step was to calculate the coefficients to correct the sensor unit temperature data. This was done as a linear regression to determine the slope and intercept for the calibration function for each thermistor. Figure 3 shows a visual portrayal of the calibration process for one of the sensor units.

Figure 3: Example of Calibration Calculations



A total of 21 houses were monitored, with 5–21 end uses metered in each, with a median of nine end uses per house. At each house, the researchers followed the same protocol for installation: meeting with the homeowner, walking through with the homeowner, installing the sensor unit, installing the wireless sensor network, and a presenting a summary of the installation to the homeowner. The procedure and overview was explained to the homeowner, and the homeowner was reassured that the Internet connection would be only minimally affected by the data transmission. For example, even with AT&T's slowest DSL service, the data transmission rate would be less than 1 percent of the upload bandwidth. The field research staff also asked the homeowner about any special concerns, such as off-limit areas in the home or not disturbing children or pets.

The field research staff and plumber then conducted a general walkthrough of the home to identify the water end uses to be metered, and assessed the feasibility of installing the meters. If any deal-breakers arose (e.g., unsafe conditions, plumbing that would not allow meter installation) the plumber informed the field specialist. If there was no way to easily mitigate the condition, the homeowner was informed, and that house was not included in the study.

The sensor units were installed according the guidelines specified in Table 1.

Table 1: Guidelines for Installing Sensor Units

Site	Guidelines
Water Heater	Attach one sensor unit to the hot water outlet of the water heater and one to the cold water inlet.
Sink	Install two sensor units at each sink; one on the hot water line and the other on the cold water line. Sensor units were installed after the angle stop, and the mote for the two sensor units was placed beneath the sink.
Shower	Place one sensor unit between the showerhead and the shower arm. Attach the mote to the wall outside the shower.
Clothes Washer	Install two sensor units and one mote at each clothes washer.
Dishwasher	Install one sensor unit and a single mote at each dish washer.
Bathtub	Installation of sensor units on tub spouts is not feasible.

Views of some installed motes and sensor units at a water heater, shower, bathroom sink, kitchen sink, and clothes washer are shown in figures 4–8.

Figure 4: Sensor Units and Mote at Water Heater

Figure 5: Sensor Unit and Mote at Shower

Figure 6: Sensor Units and Mote at Bathroom Sink

Figure 7: Sensor Units and Motes at Kitchen Sink

Figure 8: Sensor Units and Mote at Clothes Washer

While the plumber was installing the sensor units according to protocol, the field specialist set up the communication system. Once everything was installed, the field specialist tested the data connection and functionality of the meters. Reception of temperature and flow data at the server was verified. The visit concluded by summarizing the installation for the homeowner and talking with the homeowner about how to contact the team with any questions, issues, and concerns. During the study, the researchers checked in with the homeowners periodically to inquire on the status of the installation in their home.

CHAPTER 5: Data Collection and Analysis Methodology

The HWDS monitoring systems were installed in 21 homes from July 2013 to February 2014. The field work yielded as much as eight months of data at each house. The installation process was described in an earlier memo to the Energy Commission (Lutz et al. 2013).

Tables 2 and 3 present a summary description of the monitored houses and water end uses in each house.

Table 2: General Specifications of Monitored Houses

General House Specifications								
House#	Total Occupants	Square Footage	Number of Floors	Number of Bathrooms	Year Built	Architectural Style of Home	Foundation Type	Estimated Days Data Collected
1	2	1001-1500	1	2	1904	Ranch	Crawl Space	129
2	3	1001-1500	1	1	1915	Bungalow	Crawl Space	8
3	2	1501-2000	2	3	1904	Bungalow	Crawl Space	114
4	3	2001-3000	1	3	2011	Ranch	Crawl Space	147
5	2	1501-2000	2	3	1935	Bungalow	Crawl Space	114
6	2	2001-3000	2	3	1967	2 story, attached garage	Crawl Space	75
7	2	1001-1500	2	2	1985	Split-Level	Slab and Crawlspace	90
9	2	2001-3000	1	2	1968	Ranch	Crawl Space	100
10	4	1001-1500	1	2	1981	Unknown	Slab Foundation	60
11	2	> 3000	2	3	1994	Contemporary	Slab Foundation	205
13	3	1501-2000	2	2	1909	Traditional Farmhouse	Crawl Space	140
14	4	2001-3000	2	3	2003	Bungalow	Crawl Space	70
16	2	1001-1500	1	1	1951	Post-WWII	Crawl Space	140
17	4	1501-2000	1	2	1970	Ranch	Crawl Space	195
18	5	> 3000	2	5	2008	Contemporary	Slab Foundation	180
19	1	1001-1500	3	2	2005	Townhouse	Slab Foundation	53
20	5	2001-3000	2	3	2000	Contemporary	Slab Foundation	40
21	3	2001-3000	1	2	1975	Ranch	Slab Foundation	165
22	2	1501-2000	1	3	1962	Single story, arch roof	Slab Foundation	135
24	3	1001-1500	2	1	1930	Crafstman	Basement	130

Table 3: Water End Uses in Monitored Houses

Water End Uses											
House#	Water Heater Type	Water Heater Location	Total Indoor Uses (metered)	Bathroom Sinks	Toilets (#) = metered	Showers	Bathtubs	Kitchen Sinks	Dish Washer	Clothes Washer	Garage/ Laundry Sink
1	Gas-Storage Tank	Kitchen Closet	9	2	2	2	2	1	1	1	0
2	Gas-Storage Tank	Outdoors	6	1	1	1	1	1	1	1	0
3	Gas-Storage Tank	Inside, Near Kitchen	11	3	3	2	2	1	1	1	0
4	Gas-On-demand	Outdoors	10	5	3 (0)	2	1	1	1	1	0
5	Gas-Storage Tank	Crawl Space	11	3	3	2	2	1	1	1	0
6	Gas-Storage Tank	Closet-Side of House	14	5	3	2	1	1	1	1	1
7	Gas-Storage Tank	Garage	9	2	2	2	1	1	1	1	0
9	Gas-Storage Tank	Garage	11	4	2	2	1	1	1	1	0
10	Gas-Storage Tank	Garage	8	2	2 (0)	2	1	1	1	1	1
11	Gas-Storage Tank	Closet-Side of House	13	4	3 (0)	2	1	1	1	1	1
13	Gas-Storage/On-demand	Outdoors	7	2	2 (0)	2	1	1	1	1	0
14	Gas-Storage Tank	Closet	13	3	3	2	2	1	1	1	0
16	Gas-Storage Tank	Garage	5	1	1 (0)	1	1	1	1	1	0
17	Gas-Storage Tank	Garage	5	2	2 (0)	2 (0)	1 (0)	1	1	1	1 (0)
18	Gas-Storage Tank	Garage	21	7	5	4	3	1	1	1	2
19	Gas-Storage Tank	Garage	8	2	2	1	1	1	1	1	0
20	Gas-Storage Tank	Closet-Side of House	15	5	3	3	1	1	1	1	1
21	Gas-Storage Tank	Laundry Room	9	2	2 (0)	3	2	1	1	1	1
22	Gas-Storage Tank	Outdoors	9	3	3 (0)	3	1	1	1	1	0
24	Gas-Storage Tank	Basement	7	1	1	1	1	1	1	1	2 (1)

Occasionally an anomalous temperature or flow rate was recorded. Obviously inaccurate data readings were detected and deleted. If the inaccurate readings were sporadic and did not appear to indicate any systematic error, they were modified to reflect reasonable values or deleted. Table 4 shows the limits of credible data. The flow rate limits are based on the manufacturer specifications for the turbine insert. The temperature limits are for liquid water at atmospheric pressure.

Table 4: Limits of Credible Data

	Too Low	**Too High**
Flow	< 0.25 GPM (0.95 L/min)	> 8.00 GPM (30.3 L/min)
Temperature	≤ 32°F (0°C)	≥ 212°F (100°C)

GPM = gallons per minute; L/min = liters per minute

Due to an undiagnosed systematic error in the data acquisition system, many records of no flow were recorded as -0.01 gallons per minute (GPM). All data indicating flow rates at this level were reset to 0.0 GPM.

Detecting inoperative flow meters is not just a matter of not recording any flow at the water heater or at any end use. Water use is only initiated in response to the residents' behavior, so it is possible that they were not using water at any end use during the period in question. Examples are unused bathrooms or times when no one is home. An indication of an inoperative flow meter, instead of a lack of water use, would be if the water temperature were to change quickly with no recorded water flow. Changes of temperature of more than a few degrees per minute without an associated water flow being recorded should be investigated further.

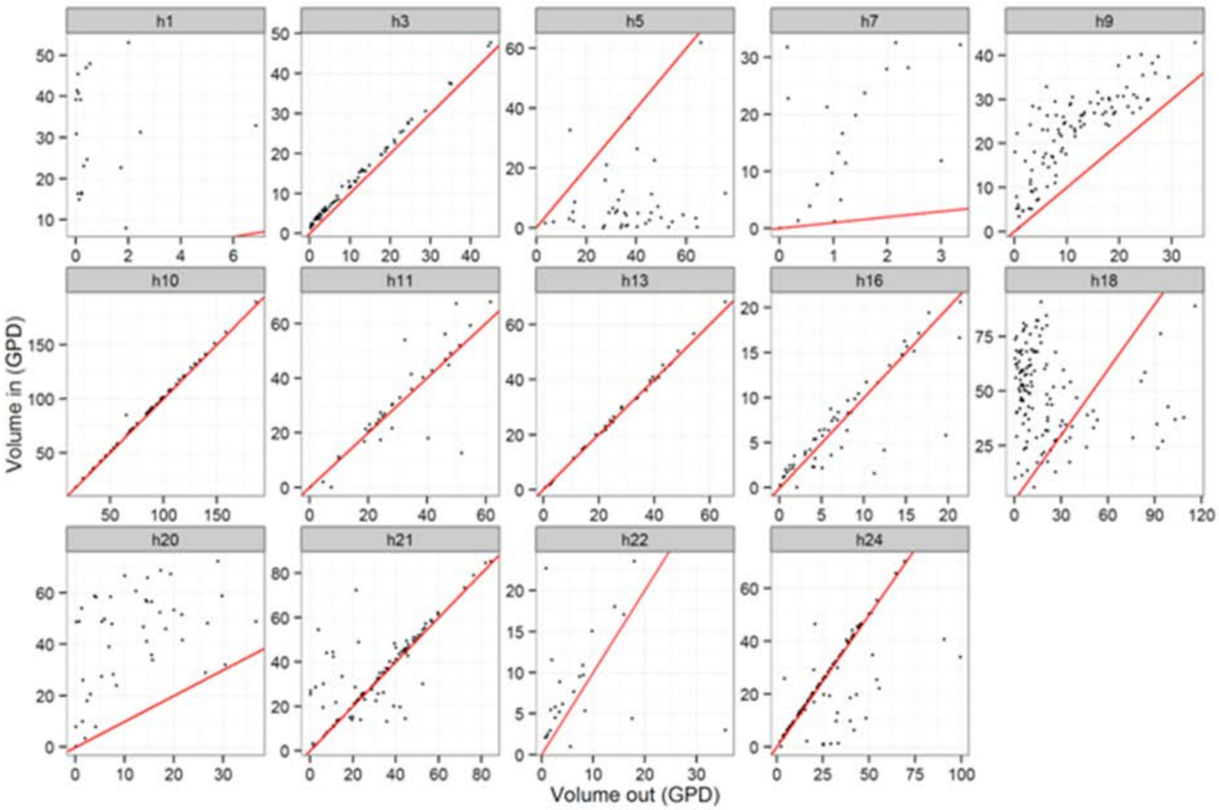
However, a temperature change cannot be expected with every draw. It is entirely possible that the line supplying an end use is long enough so hot water from the water heater does not arrive at the end use before that draw ends. When it has been a sufficiently long time since the previous draw, all the water in the line will have reached ambient room temperature. In this case, for a short draw, there would be water flow with no change in water temperature and searching for temperature changes won't be successful.

Once the data havehas been screened and cleaned by the quality assurance steps, there are several data analysis tasks that can be done. The data analysis tasks can be roughly divided into topic areas of water flow volume and temperature, and energy.

The daily volumes of water measured at the inlet and outlet of the water heater were compared for each house. The total amount of water entering the water heater may differ slightly from the total volume of water leaving the water heater, for a variety of plumbing reasons. If there is no check valve on the house water meter (or an expansion tank has been installed instead) then water can flow back out of the water heater due to thermal expansion. If there is a large draw, the tank will fill with cold water. As that cold water is heated, it will expand. The extra volume of water has to go somewhere. If there are no draws, the pressure will force some water back into the cold water plumbing. Another possibility is that a pressure drop on the cold water side will release water out of the tank back into the cold water plumbing. A large cold water draw elsewhere in the house, or even outside the house could reduce the cold water pressure. In both of these cases, water would be going out the cold line of the water heater. Since the turbine inserts in the sensor units are not able to distinguish which way the water is flowing, it appears more water came into the tank from the cold water line than left via the hot water line. Figure 9 shows a comparison of the total daily flow into and out of each water heater.

Clearly there were problems with the outlet flow meters at houses one, seven, and 20.

Figure 9: Daily Volume of Water Measured at the Inlet and Outlet of the Water Heater by House



The daily sum of all the hot water measured at the end uses did not necessarily match the daily total flow from the water heater. The research team did not measure hot water flow at two end uses: showerheads and bathtub spouts. At the showerheads, the measured flow is mixed hot and cold water, so the fraction of hot water in the flow depends on the mixing ratio of hot to cold water. As for the bathtub spouts, it was not feasible to install sensor units for this study at each tub spout without major/irreversible alteration to the house and plumbing. Therefore this project did not measure any water, hot or cold, that was delivered directly to bathtubs. If no other flow meters were indicating flow and hot water was leaving the water heater, it is likely that it was going out a tub spout, especially if it was followed directly by a shower.

Indoor hot water uses can be characterized as temperature-dependent uses or volume-dependent uses. Temperature-dependent uses are ones where the user has a desired temperature in mind. The best examples of this are showering and washing at sinks. Volume-dependent hot water uses are typically draws by machines such as dishwashers or washing machines. These machines will draw the requisite amount of water, regardless of the temperature.

Dishwashers are rated for energy efficiency under a test protocol that supplies an inlet water temperature of 140°F (60 °C) (10 C.F.R § 431). Dishwashers have internal heaters to ensure that the water temperature is adequate for cleaning. If the temperature of the water a dishwasher uses in the field is less than the temperature measured when it is tested, the energy efficiency of the dishwasher in the field will be less than the rated efficiency. A weighted average temperature of the hot water drawn for entire dishwashing cycles can be calculated. This field temperature can be compared with the temperature specified in the test protocol to see how well the test procedure matches field conditions.

Hot water use is very sporadic. If a draw starts after the water in the distribution system has cooled off, for the first part of the draw the end use will not be receiving hot water. The distribution system will not be efficient at delivering hot water. Thus the energy efficiency of the hot water distribution system depends on the timing of hot water uses, as well as the configuration and insulation levels.

The energy content (enthalpy) of water flowing through a sensor unit can be calculated. The enthalpy is determined relative to a reference temperature. Using the energy content of the water at the outlet of the water heater and the energy content of the water at the end uses, the energy efficiency of the hot water distribution system can be calculated. The efficiency can be calculated for the entire hot water distribution system of a house for one or more days, or for just one draw or end use.

CHAPTER 6: Results, Benefits to Ratepayers, Conclusions, and Recommendations

6.1 Results

6.1.1 Shower Efficiency

Calculating the energy and water efficiency of a shower event requires several steps. One additional step is to determine the useful portion of the shower event. The useful portion can be considered as the time when the user is actually in the water. The heated water consumed before the user is actually showering is entirely wasted. The time the showering started can be estimated as the time when both the temperature and flow of water at the showerhead become stable, with a temperature in the range of 95°F to 105°F (35°C to 40.5°C).

Because the sensor unit is mounted at the showerhead, the flow is a mix of hot and cold water. Part of the energy content of that water is from the cold water line, which may have been heated by the indoor conditions. For energy calculations of water used in showers, a reasonable reference temperature is the temperature of the cold water entering the water heater at the end of the shower. This would be the temperature of water coming directly from the water supply, as it will not have had a chance to pick up heat from the house or the water heater.

When analyzing shower data at each house, the distinction should be made between showers with a diverter (usually a bathtub/shower stall combination) and ones without (open or stall type showers). Most showers in the study have a tub spout with a diverter to channel water to the showerhead. This is important to note because people routinely run water through the tub spout until hot, and then adjust the temperature before diverting water through the showerhead to start their shower. Sensor units connected at the showerhead of this type of shower will not capture these initial events. Data from open or stall type showerheads will be able to measure this behavior directly. The other way to capture these data is at the water heater (for hot water flow) prior to and during shower events.

The water efficiency of a shower event can be calculated according to the following equation.

$$\eta_{water} = \frac{\sum_{showering}(V_{showerhead})}{\sum_{waterheater}^{until\ showerhead}(V_{waterheater.out}) + \sum_{showerhead} V_{showerhead}}$$

where;

$V_{showerhead}$ = volume of water at the showerhead, and
$V_{waterheater.out}$ = volume of hot water leaving the water heater.

The sum in the numerator of the water efficiency equation is the total amount of water leaving the showerhead during the time when the user is actually showering. The sums in the denominator are the total amount of water at the showerhead during the shower event and the hot water at the tub spout prior to the shower. Because water was not measured at the tub spout, the amount of water can be approximated by the flow of water from the water heater just prior to flow at the showerhead. The volume of flow at any other hot water end uses during this time must be subtracted.

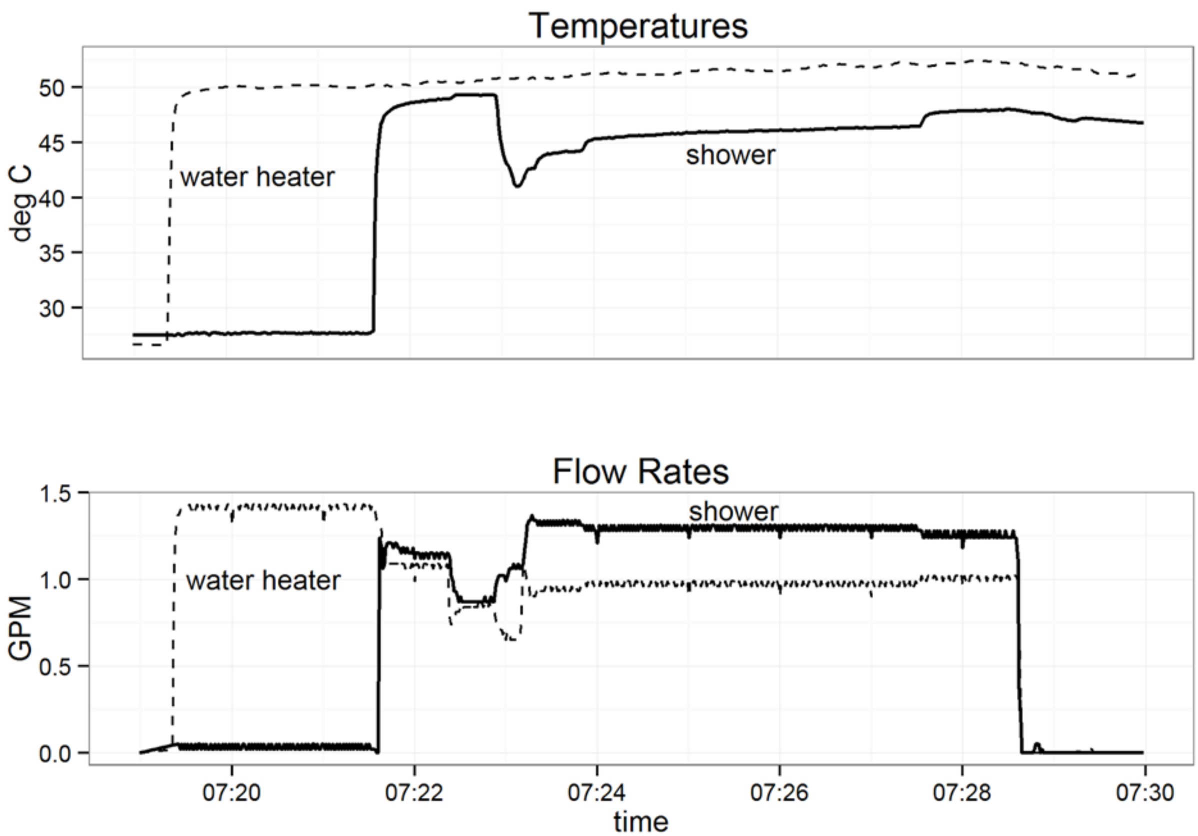
The energy efficiency of the hot water distribution system for a shower event is similarly the energy content of only the water at the showerhead during the actual showering divided by the energy content of all the water leaving the water heater for the showering event. The equation for the energy efficiency of a shower event is:

Figure 10 shows a shower event at 7:19 am. The upper panel shows water temperatures; the lower panel shows flow rates. The dashed traces show flow rate and temperature leaving the water heater. The solid traces show the temperature and flow rate at the showerhead.

This shower event can be divided into several activity segments. The first segment begins at 7:19:23 when water is turned on full hot. At this point nearly the entire flow of hot water, 1.4 GPM (5.3 L/min), is through the tub spout. Only a very slight amount of water flows through the showerhead. At 7:21:38 the tub spout diverter is closed and water starts flowing to the showerhead. The extra resistance of the showerhead in the water path reduces the flow out of the water heater to 1.09 GPM (4.13 L/min). A slight amount of cold water is still flowing to the showerhead. Mixed water is flowing through the showerhead at 1.12 GPM (4.24 L/min), but only 1.09 GPM (4.13 L/min) is leaving the water heater. At 7:22:22 the person using the shower started adjusting the temperature by changing the mix of hot and cold water. At 7:23:21 the flow rates stabilize with only two minor subsequent adjustments, to modify the temperature slightly, until the end of the shower at 7:28:36. The temperature of the water in both the pipes slowly decays after the water stops flowing.

The segment of stable temperature and water flow—5 minutes and 15 seconds—was assumed to be the useful portion of the shower. The entire event lasted 9 minutes and 13 seconds. All the water used before the shower segment started, at 7:23:21, was wasted. And the energy that had heated the hot water used before that time was also wasted.

Figure 10: Water Temperature and Flow Rate During a Shower Event



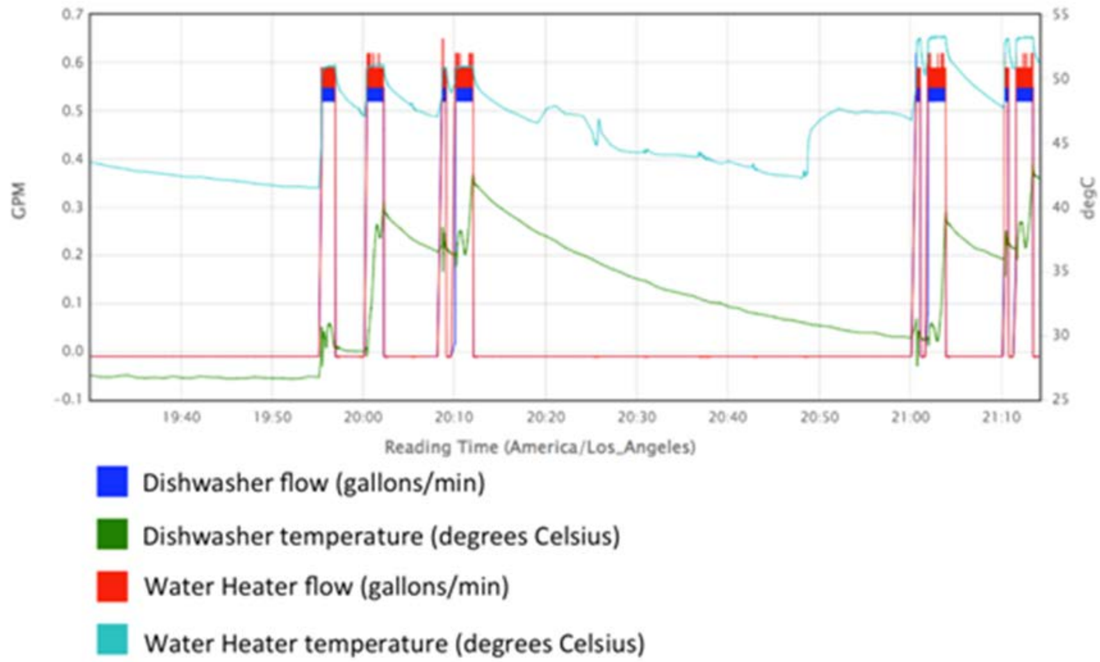
The energy efficiency of the HWDS during this shower was calculated to be 53.8 percent.

These methods of calculating the water and energy efficiency of shower events are approximate, as the calculations do not include leaks at the tub spout diverter. Pressure-compensating shower valves allow a certain amount of cold water through the valve, even when turned to full hot, to prevent accidental scalding.

6.1.2 Dishwasher Event

Figure 11 shows an example of a set of draws for one dishwasher cycle. During this cycle the water temperature does not consistently reach a high enough temperature to be used without further heating before the draws end. The longer draws are approximately two minutes, while the shorter draws are approximately one minute. The volumes of each draw from the water heater closely match the volume measured at the dishwasher matches.

Figure 11. Set of Dishwasher Draw Events



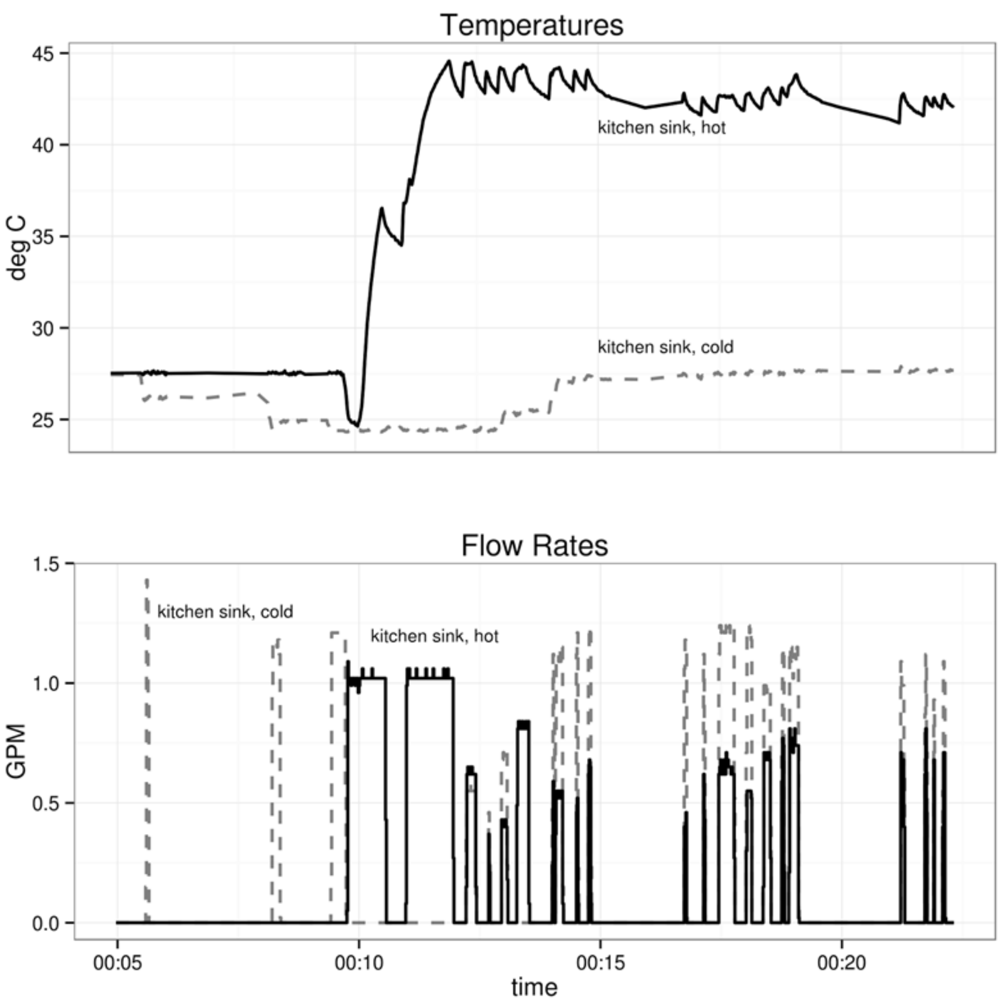
The total energy in the water entering the dishwasher was 1,444 Btu (1,523 kilojoules, kJ) for these draws. The total volume water that passed through the flow meters was 5.66 gallons. The total energy in the water leaving the water heater (only when there was flow at the dishwasher) was 3,043 Btu (3,211 kJ). The total volume of water that passed through the water heater meter was 5.95 gallons. The average temperature of the water leaving the water heater during draws was 45°C. The delivered energy efficiency of the HWDS for this set of events was 47.4 percent. This study makes a case that using hot water for this dishwasher is very inefficient. The dishwasher draws are so short; the unit does not receive hot water until the end of the last draw in each set. This requires the dishwasher to provide its own water heating at the end use.

6.1.3 Kitchen Sink Event

Figure 12 shows data recorded during a series of water draws at a kitchen sink. The upper portion shows temperatures; the lower portion shows flow rates. The dashed trace is water flow and temperature at the cold water line to the faucet at the kitchen sink. The solid trace is the hot water line to the faucet.

This series of events begins with a two-second draw of cold water flow at 0:05:36. It is followed by two cold water draws of 1.18 and 1.21 GPM (4.47 and 4.58 L/min) three and four minutes later. The third cold water draw is followed almost immediately by a 45-second hot water draw at 1.02 GPM (3.86 L/min). Thirty seconds later it is followed by another one-minute hot water draw at 1.02 GPM (3.86 L/min). After that there are 18 short draws in the next ten minutes. None of those draws lasts longer than 15 seconds. The hot water at the faucet does not get hot until the end of the second hot water draw, after nearly two gallons have been drawn. All but one of the 18 draws after the hot water draws are a mixture of hot and cold water, indicating water is at the desired temperature. The consistent ratio of hot and cold water show this is likely a single-lever faucet.

Figure 12: Water Temperature and Flow Rate during a Kitchen Sink Event



This pattern of hot water use is suggestive of someone cleaning dishes by hand. It is plausible that the two initial hot water draws were intended to bring hot water to the faucet or to fill a tub. No water had been used at the kitchen sink for several hours prior to these draws. The temperature in the hot and cold faucets had stabilized to room temperature over this time. The temperature of the cold water draws dropped 3°C (5.4°F) for about ten minutes, and then returned to room temperature. One likely explanation is that most of the cold water pipe was within the building envelope and had reached room temperature. A small segment of that pipe may run closer to the outside wall. It would have lost more heat to the exterior than the pipes inside the building.

The total energy of the hot water at the kitchen sink is 316 Btu (333 kJ) with a total volume of 3.05 gallons of water. The total energy in the water leaving the water heater (only when there was hot water flow at the kitchen sink) for these events was 604 Btu (637 kJ). The delivered energy efficiency of the HWDS for this set of events is 52.3 percent.

6.2 Recommendations

Preliminary analysis of the results of this research suggests that the efficiency of HWDS in California homes can be disturbingly low. Further analysis of the impact of the HWDS should be used to inform the revisions the plumbing codes and the building energy efficiency codes.

Simulation Modeling. One of the additional uses for data gathered from this study is to improve hot water distribution system simulation modeling tools. As part of another task in this PIER project, LBNL developed a computer simulation modeling tool for hot water distribution systems (Grant and Lutz 2013). The monitoring in the current task was done in existing buildings. We were not able to directly determine detailed characteristics of the plumbing systems, such as the layout, length, diameter, and material of the hot- and cold-water pipes. However, it should be possible to reverse-engineer the key characteristics of the hot water distribution system. This could be done by imposing the flow rates of the observed draw patterns on a simplified model of the HWDS and comparing the temperature profiles at the end uses in the simulation to the observed temperature profiles. By iteratively adjusting the characteristics of the links in the plumbing tree until the simulated temperature profiles best match the observed temperature profiles, it would be possible to calculate an optimized simplified model of the HWDS for each house. These simplified simulation models could be used for creating design guidelines or improving building energy-efficiency standards.

6.3 Benefits to Ratepayers

This research project investigated the waste of water and energy due to poorly performing HWDS in existing California homes. Benefits to ratepayers will come from improved HWDS designs for new homes and major retrofits to existing homes based on the findings of this research. The plumbing and building energy-efficiency codes can be upgraded to reflect these findings as well.

6.4 Conclusions

Lawrence Berkeley National Laboratory has developed a wireless sensor network technology to measure water temperature and flow rate at indoor end uses. These networks were successfully deployed in 21 houses. Water flow and temperature data were successfully collected and uploaded to a data server.

Preliminary analysis demonstrates that for some shower, kitchen sink, and dishwasher events, only half of the hot water energy inserted into the HWDS at the water heater is actually being delivered at the end use. This finding supports the notion that there is opportunity to improve HWDS design.

GLOSSARY

Term	Definition
Btu	British thermal unit
DOE	U.S. Department of Energy
DSL	Digital Subscriber Line
GPM	Gallons per Minute
HWDS	Hot Water Distribution System
kJ	Kilojoules
L/min	Liters per minute
LBNL	Lawrence Berkeley National Laboratory
PAC	Program Advisory Committee
PIER	Public Interest Energy Research, California Energy Commission
RECS	Residential Energy Consumption Survey
WSN	Wireless Sensor Network

REFERENCES

10 C.F.R. § 431. Energy Efficiency Program for Certain Commercial and Industrial Equipment, Title 10 *Code of Federal Regulations*, Pt. 431. 2014 ed.

Grant, Peter; James Lutz. HWDS Simulation Model Report. Lawrence Berkeley National Laboratory for California Energy Commission, April 26, 2013.

KEMA Inc. 2010. California Residential Appliance Saturation Study, Executive Summary, October 2010. http://www.energy.ca.gov/2010publications/CEC-200-2010-004/CEC-200-2010-004-ES.PDF.

Kempton, Willett. "Residential Hot Water: A Behaviorally-Driven System." *Energy* 13, no. 1 (January 1988): 107–14. doi:10.1016/0360-5442(88)90083-7.

Lanzisera, Steven, Stephen Dawson-Haggerty, H. Y. Iris Cheung, Jay Taneja, David Culler, and Richard Brown. "Methods for Detailed Energy Data Collection of Miscellaneous and Electronic Loads in a Commercial Office Building." *Building and Environment* 65 (July 2013): 170–77. doi:10.1016/j.buildenv.2013.03.025.

Lanzisera, Steven, and James Lutz. Initial Prototype Wireless Sensor Network Specifications. Lawrence Berkeley National Laboratory for the California Energy Commission, April 2, 2012.

Lutz, Jim, Steven Lanzisera, Anna Liao, Chris Stiles, and Margarita Kloss. Wireless Sensor Networks Deployment Memo. Memo. Lawrence Berkeley National Laboratory for California Energy Commission, July 26, 2013.

Lutz, Jim. "Water and Energy Wasted During Residential Shower Events: Findings from a Pilot Field Study of Hot Water Distribution Systems." In ASHRAE Transactions, 118:, Part 1:11, 2011. http://www.escholarship.org/uc/item/5209d7pf.

Lutz, James, Peter Biermayer, and Derek King. *Pilot Phase of a Field Study to Determine Waste of Water and Energy in Residential Hot Water Distribution Systems.* Sacramento, CA: Lawrence Berkeley National Laboratory for the California Energy Commission, July 2009. http://www.energy.ca.gov/2013publications/CEC-500-2013-135/CEC-500-2013-135.pdf.

RECS 2009, U.S. Energy Information Administration. 2009 RECS Survey Data, Housing characteristics tables, Appliances. http://www.eia.gov/consumption/residential/data/2009/xls/HC3.3 Appliances by Year of Construction.xls.

APPENDIX A: Lessons Learned

During the course of this project several lessons were learned that should be considered by anyone attempting to do similar research. Some of the issues were specific to the design of the sensor unit and wireless sensor network that were used in this project.

Survey/Human Subjects/Recruiting Houses

It can not be stressed enough how important it is to have a reliable, robust data collection system. One of the biggest challenges to minimizing data gaps was scheduling visits with the homeowners to address issues that could not be resolved remotely. In most cases the actual time needed to identify, diagnose, and make repairs to get the data point(s) back on line took hours at most. Difficulties with scheduling visits often caused gaps in data for periods of days or sometimes weeks. To minimize the need for visits, several IT-related solutions or tools were implemented during the study that should be further developed.

Sensor Unit Hardware

Use high-temperature glue (at least 300 °F) to attach the thermistor and turbine insert retainer. Some of the installations were exposed to 180 °F water for many weeks.

Round off the chamfer at the end of the threaded inlet and outlet pipes. The sharp edge damages the washers in the flex line connectors.

Mote Design

Design the mote to maximize battery life. Some of the motes, particularly ones at the water heater, drained the battery faster than anticipated. It is important to design the antenna to improve signal reception.

Data Acquisition

The embedded computer and manager mote should be designed to recover from any loss of power or loss of Internet connectivity. The programming on the embedded computer should also periodically update its internal clock. A script to automatically restart the manager and sMAP processes daily would be helpful.

Calibration

Store the reference water temperatures and flow rates used during the sensor unit calibration on the sMAP server. That way the sensor unit and reference data will be available together.

The sensor ID number should be written on the outside of the sensor unit during the calibration process. This will facilitate later tracking of which sensor unit was recording data at which end use.

Data Quality Assurance

Create a script to generate a daily status log before the first WSN is installed. It is crucial that this log is checked daily by the person who is responsible for correcting any problems. The script should check that every WSN is posting data. The temperature and flow data from every sensor unit should also be checked.

As soon as motes are installed, tag the data stream from each sensor unit with the end use to which it is connected (e.g., Water Heater Hot, Water Heater Cold, Dishwasher)

Installation

Estimate the pipe length to each end use from the water heater. Make detailed notes about appliances brand/model/make, etc. Take photos of the installation at every end use.

Uninstallation

Save and label all parts if needed for further analysis.