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## **Pilot Phase of a Field Study to Determine Waste of Water and Energy in Residential Hot-Water Distribution Systems**

Jim D. Lutz and Peter Biermayer

Energy Analysis Department  
Lawrence Berkeley National Laboratory  
Berkeley, CA 94720

Derek A. King

4D Imaging, Inc.  
Berkeley, California

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# **Pilot Phase of a Field Study to Determine Waste of Water and Energy in Residential Hot Water Distribution Systems**

**James D. Lutz, P.E.**  
*Member ASHRAE*

**Peter Biermayer**  
*Associate Member ASHRAE*

**Derek A. King**

James D. Lutz is a research associate supervisor in the Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, California.

Peter Biermayer is a staff research associate in the Environmental Energy Technologies Division, Lawrence Berkeley National Laboratory, Berkeley, California.

Derek King is an engineer at 4D Imaging, Berkeley, California.

# Pilot Phase of a Field Study to Determine Waste of Water and Energy in Residential Hot Water Distribution Systems

## ABSTRACT

*This paper provides an overview of the pilot phase of a field study to determine the feasibility of a method of directly measuring the waste of water and energy caused by current hot water distribution systems (HWDS) in California residences using wireless sensor network technologies. The experience gained in the pilot phase study using wireless sensor networks demonstrates that it is clearly feasible to use this technology for measuring water and gas flows and temperatures.*

*The goal was to demonstrate a method to reliably collect water flow and temperature data from every indoor hot water end use point, at the water heater in one second intervals when water was flowing. The overall success of the pilot phase study indicates that this technique can work. However, the pilot phase study did reveal shortcomings in many areas. The recommendations in this paper address those shortcomings and provide ways to improve the outcomes of any follow-on field study. The project's tasks were to test and evaluate the proposed hardware, installation protocols, data collection, and processing procedures. The techniques developed in this project provide a way to accurately measure temperature and flow of indoor water use events at one second resolution. The technologies used in this pilot phase study are viable for use in a larger field study to determine the energy and water efficiency of hot water distribution systems in California homes. The lessons learned from this experience will improve procedures, programming and wireless sensor network specifications.*

## INTRODUCTION

California's energy and water resources are both at a premium, and the state's economic and environmental vitality depend on the efficient use of these resources. Heating water is one of the most

energy-consumptive activities in a household, accounting for about 40% of California residential natural gas consumption. In terms of water use, water heating system designs often require users to run the water for a time before it achieves the desired temperature, wasting water in the process.

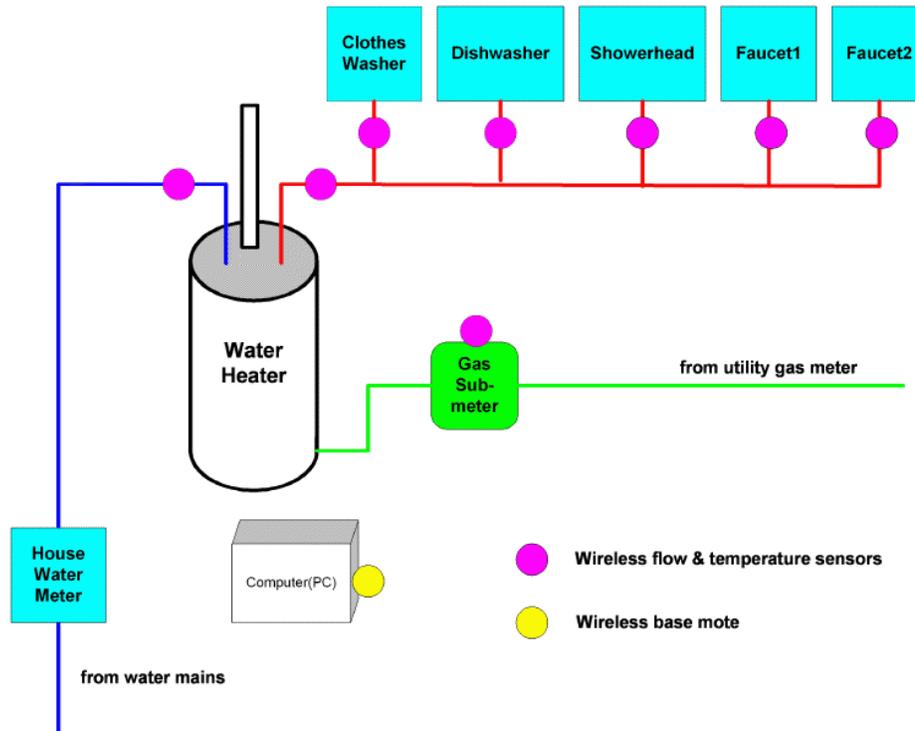
The purpose of this project was to conduct a pilot study to determine the feasibility of a method to directly measure the waste of water and energy caused by current hot water distribution systems in California residences using wireless sensor network technologies. Monitoring of hot water end uses in residential buildings has been done before. (Lowenstein, 1996. Lowenstein, 1998. Tiller, 2004) However those studies did not investigate the efficiency of the HWDS. This project explored a methodology to determine the efficiency of the HWDS.

This project sought to gain experience with the field measurement process and collect actual data to understand the automated collection and processing protocol necessary to measure the waste of water and energy caused by current residential hot water distribution systems

Monitoring was successfully completed on three houses for a total of 22 days. Activities included equipment installation, and monitoring at the water heater and hot water end uses.

## **APPROACH**

A wireless sensor network was developed to measure flow and temperature of water at the trunk (water heater) and twigs (individual end-use points) of a residential HWDS. Data were collected at one-second intervals while hot water was flowing. The points in the HWDS that were monitored were the inlet and outlet of the water heater and several hot water end-uses in single-family residences. The collected data were minimally processed on site and sent to a central server by cell modem for further processing. At the central data processing site, the one second interval field data were analyzed and aggregated into summary data about individual hot water draws.



*Figure 1 Measurement points*

All measurements were taken at points that are capable of being isolated by shutoff valves, such as sink faucets and clothes washers. This strategy allowed relatively simple installation. The appropriate shutoff valve was closed, the downstream plumbing was disconnected, the flow meter and thermistor mountings were installed, and the plumbing was reconnected. Similar flow and temperature monitoring equipment was applied to the gas line supplying the water heater to measure energy use by the water heater.

The temperature and flow of water was measured into and out of the water heater and at the clothes washer, dishwasher, showerhead, and kitchen sink faucet. The temperature and flow of gas to the water heater was also measured. Figure 1 shows the points at which temperatures and flows were measured.

### Monitoring Equipment

Water flow was measured with an inline turbine meter. The flow meter is manufactured for use in tankless water heaters. It is small enough to be installed without trouble in most locations.

The standard pickup for the flow meter is a Hall sensor, which detects a magnetic pulse each revolution from a magnet mounted on the turbine blades. Another type of pickup, a Wiegand sensor was available from the manufacture. Unlike a Hall sensor, this type of sensor does not need external power. The Wiegand sensor pickoff worked well with the equipment used in this study. No modifications to the data acquisition software or hardware were necessary to use the Wiegand sensor. Since energy management is an issue for the wireless sensor network, the Wiegand sensors were used to conserve energy and extend battery lifetime.

The output of the flow meters is rated at 515 pulses per liter (1950 pulses per gallon) at flow rates above 2 liter/minute (0.5 GPM), with a full scale linearity of 1% over a range from 1.0 to 30 liter/minute (0.26 to 7.9 GPM). (Sika, 2006) Since many of residential hot water flows at end uses are below the lower rate, the flow meters were calibrated in the laboratory. Below about 0.5 liter/minute (0.13 GPM) the flow meter does not register any flow. Figure 2 is a sample calibration curve for one of the flow meters. At a 2 liter per minute flow rate the 0.002 liter per pulse (515 pulses per liter) is equivalent to  $\pm 1\%$  accuracy. Unfortunately the accuracy decreases dramatically at lower flow rates.

Temperature was measured with a thermistor probe inserted into the water flow. Thermistors are ceramic semiconductors whose resistance drops nonlinearly as temperatures rise. The thermistors used for this project were rated at 10,000 ohm ( $\Omega$ ) resistance at 25°C (77 °F ) with a tolerance of  $\pm 0.2^\circ\text{C}$  ( $0^\circ\text{C}$  to 70° C) ( $\pm 0.4^\circ\text{F}$  (32°F to 158 °F)),(QTI, 2005) Although the configuration of the probes and the thermistor specifications were chosen to maximize temporal sensitivity, measurements were not taken during the project to determine the time constant.(Linkous 2007)

For this project, temperature was determined by measuring the resistance of the thermistor and applying the following equation:

$$\frac{1}{T} = a + b \ln(R_{therm}) + c(\ln(R_{therm}))^2 + d(\ln(R_{therm}))^3$$

where;

$T$  = temperature (kelvins),

$a = 0.001116$

$$b = 0.00023$$

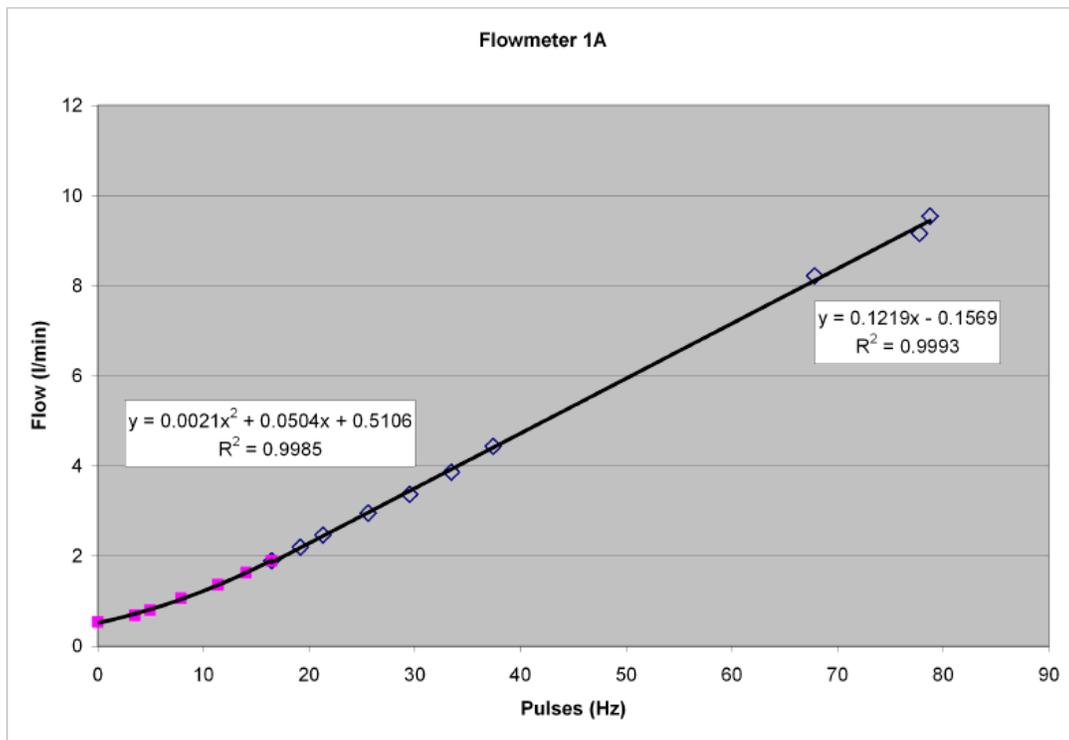
$$c = -0.0000003723$$

$$d = 0.00000009906$$

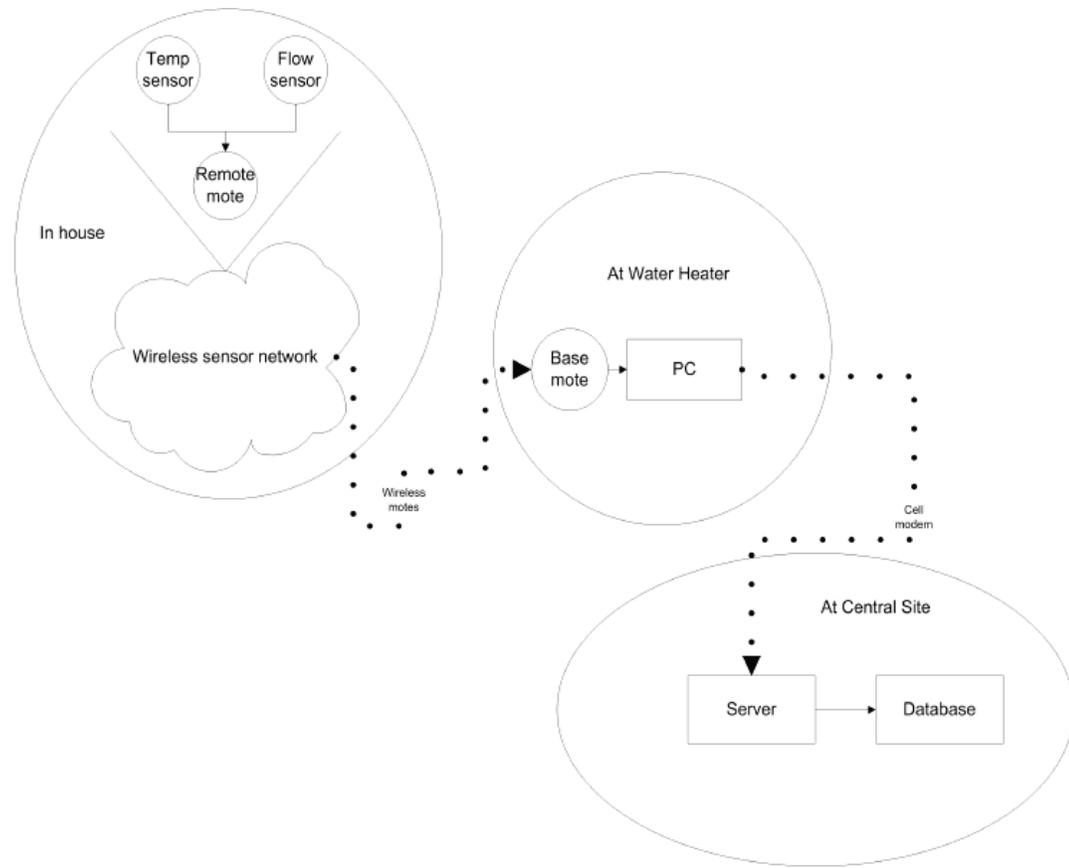
$R_{therm}$  = resistance of thermistor (Ohms).

This raises the possibility of higher flows due to coincident uses of hot water at different end use points. During concurrent hot water draws at different end uses, the flow of water at the water heater will be the sum of these flows. Because of the potentially higher flow rates at the water heater, a different flowmeter was used at that location.

The flow meters used at the inlet and outlet at the water heater were a rotor design with a single jet. They had a rated range of 0.8 to 38 liters per minute (0.3 to 10 GPM). The accuracy of these flow meters was listed as  $\pm 1\%$  full scale by the manufacturer.



**Figure 2** Calibration curve for flowmeter 1A.



**Figure 3** Data collection and transmission scheme.

The output of these flow meters was a square-wave pulsed voltage, at 87.2 pulses per liter (330 pulses per gallon). Since the output of these flow meters was also in pulses, the identical data acquisition system was used to read the output of these meters.

An auxiliary gas meter was installed on the gas line to the water heater to record gas use by the water heater. A magnetic pulse generator attached to the gas meter generated 17.7 pulses per liter (500 pulses per cu.ft.). Gas consumption during gas draw events was recorded at one second intervals. The pilot light to ignite the main burner of water heaters burns continuously. The gas use by the pilot light was recorded as single pulses at approximately 20 second intervals. For a complete knowledge of the energy consumption of the water heater, the heating value of the gas is needed. In this project the energy use of the water heater was not calculated.

In addition to collecting pulses from the gas flow meter the temperature of the surface of the gas pipe was also monitored. This temperature was used as a proxy for the ambient air temperature near the water heater when gas was not flowing to the burner. Ambient air temperature does not change very rapidly. This was sufficient to get a good record of the ambient temperature.

### **Wireless Data Acquisition System**

The data acquired by the sensors was read and transmitted to a local on-site computer by a wireless sensor network. The individual units of the wireless sensor network, also called motes, did minimal data processing and sent the data to a base mote at an on-site dedicated computer. More processing of the data was done at the on-site computer. The data was sent via cell modem to a server at a central location once a day. A schematic of the data collection and transmission scheme is shown in Figure 3.

The mote platforms used an embedded operating system developed specifically for wireless sensor networks (Levis 2006). The radio signal from the motes followed the IEEE 802.15.4 standard at 2.4 GHz (IEEE, 2006).

The circuit board for the motes was approximately 32 mm (1.27 in) by 65 mm (2.58 in) with a USB port at one end.

The motes assembled data in five-second intervals into packets during flow. During periods of no flow packets were sent at approximately 20-minute intervals. The data packets contain identification fields for the computer and the mote, a timestamp, five seconds of flow information, five seconds of temperature, and some clock synchronization flags.

Data acquisition software using wireless sensor networks has problems standard hard-wired data acquisition systems do not have. Among the problems faced in developing the software for the motes were: signal interference (making sure that concurrent signals from different motes did not result in data loss), time synchronization (making sure that all the motes were registering the correct time and applying corrections to the timestamp in the data packets if the mote was not time synchronized), and node reboots (making sure the motes rebooted automatically if the software running on them froze).

A base mote for the wireless sensor network was attached to a USB port on the onsite computer. The onsite computer was located near the water heater in all cases. The onsite computer unloaded the data

packets from the base mote and performed some preliminary data processing. Packets were sorted into files by mote and duplicate packets were eliminated. Retroactive time synchronization was applied if necessary.

The data was sent once per day via cell modem to a server at the central site. The scheme to process the data and transmit it to the central server included several automated scripts and batch files.

### **Monitored Houses**

Monitoring was done on four houses during the pilot period. The houses, all single-family detached homes built from 1970s through 1990s, were of volunteers. The water heater for each house is in the garage, as is standard for homes of this vintage in California. All houses are slab-on-grade. A short description of each house, along with the number of residents, is shown in Table 1.

The data collection at the house in Moraga was not successful. No transmission was received from the mote in the shower. The L-shape of the house meant that transmission from that mote would have gone through two layers of exterior siding. It is probable this prevented signal transmission. There were problems with getting data from other motes at this site as well.

### **Collected Data**

The collected data included flow rates and temperatures from hot water end use points at one second intervals during draws. The hot water use points monitored in the pilot study were kitchen sinks, showers, dishwashers, and clothes washers. Water flows into and out of the water heater were measured. Water temperature was measured at each end use point and at the inlet and outlet of the water heater. Data was only collected for those periods when draws were occurring. Table 2 lists the points where measurements were taken in pilot phase houses and the type of sensor.

Monitoring was successfully completed for a total of 22 full days at three houses. Due to the developmental nature of the data acquisition system, data from some days was not usable. The successful monitoring days and dates are listed in Table 3.

Data was collected for 9,416 water draw events. These water draw events include measurements of flow into and out of the water heater as well as at the end use points. Because of the standing pilot light, the flow meter on the gas line was sending data packets much more frequently. This resulted in 77,260 additional data packets being sent that weren't associated with water draws.

## Data Processing

The raw measurement data collected by the nodes and uploaded to the server was processed sequentially by several computer scripts. The processing was done for one day at a time. At this point the data was in multiple separate files for each node. First the data files sent over from each node were concatenated into one data file per node. Because of the uncertain nature of the wireless data transmission, occasionally multiple data packets would be received. Duplicate data packets were removed at this stage.

**Table 1 Attributes of monitored houses**

	<b>Concord</b>	<b>Richmond</b>	<b>Martinez</b>	<b>Moraga</b>
Area, estimated, m <sup>2</sup> (sq. ft.)	232 (2,500)	149 (1,600)	124 (1,330)	185 (1,990)
Stories	2	2	2	1
Baths	2.5	2.5	2.5	2
Bedrooms	4	3	3	4
Adults	2	4	2	3
Children	2	0	1	0
Foundation	slab-on-grade	slab-on-grade	slab-on-grade	slab-on-grade
Year built	1974	1990	1983	1965
Siding style	stucco	wood	stucco & composite	wood siding
Water heater location	garage	garage	garage	garage
Pipe type	copper	copper	copper	copper
Pressure reducer	None	None	Yes	None
Faucet type (at measured faucets)	single handle faucets	kitchen - single	single handle faucets	single handle faucets
To water heater, estimated piping distance, m (ft)				
Clothes washer	6.1 (20)	3.0 (10)	3.7 (12)	5.2 (17)
Dishwasher & Kitchen Sink	7.6 (25)	5.5 (18)	11.3 (37)	4.6 (15)
Shower	9.1 (30)	8.8 (29)	11.3 (37)	10.7 (35)

**Table 2 Measurement points in Pilot Phase Houses**

<b>End Use</b>	<b>Location</b>	<b>Monitored</b>	<b>Flow meter</b>	<b>Temperature</b>
Water Heater Inlet	garage	cold water	paddle	thermistor, in water
Water Heater Outlet	garage	hot water	paddle	thermistor, in water
Water Heater Gas	garage	gas	diaphragm	thermistor, outside of gas line
Kitchen Sink	kitchen	hot water	turbine	thermistor, in water
Dishwasher	kitchen	hot water	turbine	thermistor, in water
Shower	master bath	mixed water	turbine	thermistor, in water
Clothes Washer	garage	hot water	turbine	thermistor, in water

Next the information from the data packets was converted into a simpler format for analysis. In this format each record contained the data from one second; the timestamp, one flow measurement and one temperature measurement.

After this, the flow data from the motes was translated from pulses to volumes. This was based on the calibrations that were done in the laboratory. Each flow meter has a different calibration curve. The conversion of the thermistor resistances to temperature was done at the motes. For consistency, the temperature conversion should be done at this stage in the processing.

The interval data of flow and temperature of water at each measured point was then converted into information about draws. The data was processed record by record. There are four possibilities after reading a data line; a draw is about to start, a draw has ended, a draw is continuing, or a draw is not happening. A time gap longer than the one second between the timestamps from the previous and next record indicates that a draw has ended. The condition of a draw is also dependent on whether water is currently flowing or not. The algorithm used by the program to convert and aggregate the interval measurement data into draw information is shown in Figure 4, Flow Chart of Algorithm to Convert Measurements to Draws. Note that this algorithm will inadvertently split a draw into two separate draws if a data record is missed.

**Table 3 Pilot Phase Monitoring Days and Sites**

Site	Dates	Days
Concord	1/6–1/9, 1/13	5
Martinez	2/26–3/6	8
Richmond	3/19–3/26	9
Moraga	Not successful	0
total		22

The time at the start of the draw, the total duration of the draw, the total volume of water for the draw, the weighted average temperature during the draw, and the time since the previous draw were calculated and recorded for each draw. The time until hot water arrives can be calculated and recorded as well. The time to hot water will be important for determining the water efficiency of the HWDS, especially for shower draws.

## **OUTCOMES**

Information about the hot water draws is presented in this section. The efficiency calculations for a sample hot water event are explained in detail.

The daily hot water use, measured at the water heater inlet, for the monitored houses is shown in Figure 5. There is striking variation of hot water use between houses. The variability of hot water use from day to day within the same house can be quite large as well.

A summary of the hot water use per day by end use across all 3 houses is shown in table 4. Showers are the largest average daily hot water end use by volume. Of the end uses monitored here, kitchen sinks have the highest average number of draws per day.

Dishwashers were not used every day, so the daily average volume is lower than the volume of hot water used for one load of dishes. Also there are several draws for one load of dishes in a dishwasher or for one load of clothes in a clothes washer.

Because not every hot water end use was monitored, the total average daily volume of hot water end uses does not match the total average daily volume delivered from the water heater. See Figure 6, Average Daily Hot Water Flow at the Water Heater and at End Uses. Two meters were used to measure water flow

at the water heater. One meter was on the inlet and one was on the outlet. Surprisingly, the two flows were not identical. This is particularly true for the Martinez house. Several possible causes for this discrepancy are also discussed in the Recommendations section.

The average volume per draw is shown in Figure 7. From this figure it is clear that hot water draws for showers are significantly longer than draws for other end uses. However, the volume of water per draw for showers is lower than expected, especially for the Concord house. This may be due to data packets occasionally not being transmitted successfully. If a data packet in the middle of a draw did not get recorded, it would cause the appearance of two short draws instead of one longer draw. Sending totalized flow data instead of interval flow data, as discussed in the Recommendations section may allow correction of some of these problems.

### **Example End Use Details**

As an example of the details for hot water use, the following three charts show details of three end uses. This sample is for six minutes and shows use at a kitchen sink, dishwasher and clothes washer.

Figure 8, Kitchen Sink - Hot Water Flow and Temperature shows two short hot water draws were taken at the kitchen sink about a minute apart. The temperature of the delivered water was room temperature. This is the temperature the hot water in the pipes had cooled off to. The water at the faucet never got hot for these draws.

Figure 9, Dishwasher - Hot Water Flow and Temperature, shows a two minute draw of hot water for the wash cycle of a dishwasher. The flow rate is very constant through out the draw. Although it does increase in temperature, the water temperature does not get hot for this draw.

Figure 10, Clothes Washer - Hot Water Flow and Temperature, shows six individual draws by the clothes washer to fill for washing or rinsing a load. This set of draws is likely a rinse. The only other hot water the clothes washer used that day was a series of four closely spaced draws totaling 6.4 liters that ended 53 minutes before this set of draws. Unlike the dishwasher, the draws are not all at the same flow rate. The temperature of the water arriving at the clothes washer actually drops briefly as cooled off water is cleared from the line. After about 30 seconds hot water has arrived at the clothes washer. The time between draws is not long enough for the water in the line to cool off.

For comparison the flow of water out of and into the water heater for the same time are shown in Figures 11 and 12.

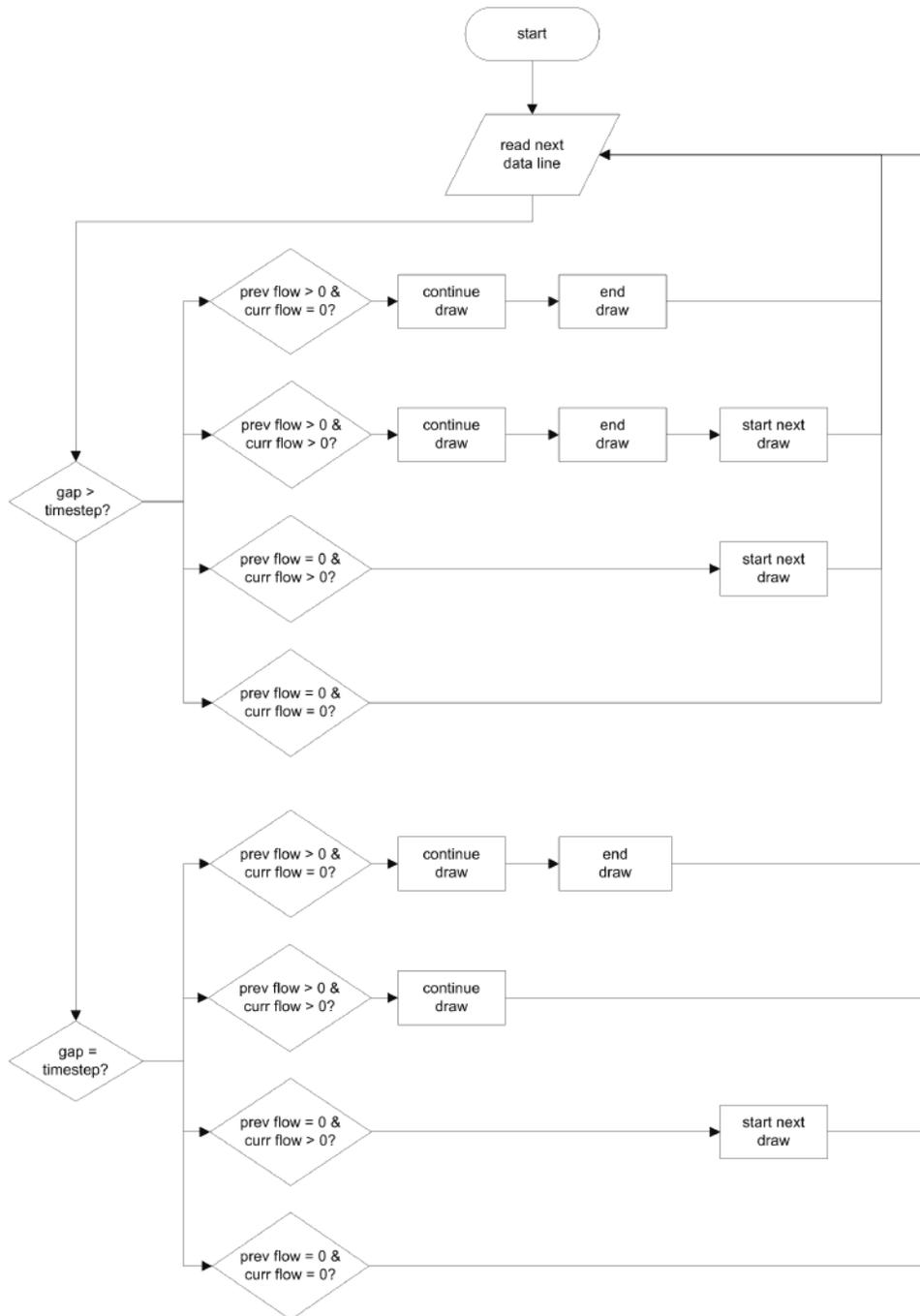
In figure 11, Flow and Temperature of Water Out of Water Heater, the three different end uses are now superposed, but still clearly visible. Even with the temperature sensor mounted near the water heater it still takes several seconds for the water temperature to rise to fully hot.

The same superposed flow pattern shown on the outlet water flow is also visible on the inlet water flow in Figure 12, Flow and Temperature of Water Into Water Heater. The pronounced drop in water temperature at the beginning of the draw shows that nearly a liter of water in the inlet line upstream of the water heater had been warmed significantly. Warming the water in this pipe contributes to the standby losses of the water heater. The lower resolution of the flow meters at the water heater meant less detail was captured at the water heater than at the end uses.

From this data the efficiency of the hot water distribution system for these draws was calculated. The efficiency of draws was calculated as the ratio of the energy out of the pipes at the end use point to the energy into the pipes at the water heater outlet. The energy was calculated as the change in enthalpy for water from 15 °C (59 °F) at atmospheric pressure multiplied by the volume of water drawn.<sup>1</sup> The volume was based on water drawn at the end use point because the flow meters at the water heater were lower resolution and were not calibrated. The reference temperature of 15 °C (59 °F), the lowest temperature seen during draws, was chosen as a representative temperature of the inlet water to the heater after the pipe had been cleared of pre-warmed water. The energy efficiency of the HWDS for these draws at the kitchen sink and by the dishwasher was about 20%. The clothes washer draw, in contrast, was over 90% efficient. results are shown in Table 5, Hot Water Distribution System Efficiencies for Selected Draws.

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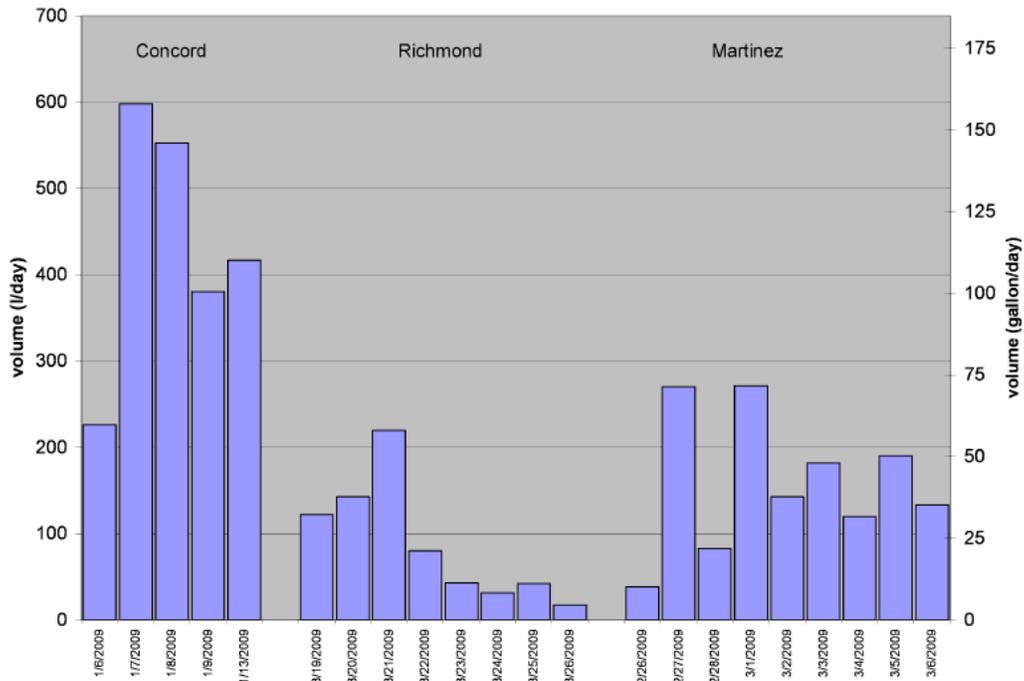
<sup>1</sup> The enthalpy and density of water were calculated from a cubic fit of data from the properties of water. (Lemmon et al. 2009).



**Figure 4** Flowchart of algorithm to convert measurements to draws.

## RECOMMENDATIONS

The following recommendations for the field study are based on the results of this pilot phase project. The experience gained in the pilot phase study using wireless sensor networks demonstrates that it is clearly feasible to use this technology for measuring water and gas flows and temperatures.



*Figure 5 Daily hot-water use.*

**Table 4 Average Hot Water Use Per Day by End Use**

location	volume liters (gallons)	draws (number)
kitchen sink	20.6 (5.4)	30.6
DW	8.5 (2.2)	3.6
shower	105.3 (27.8)	5.2
CW	7.5 (2.)	7.3

The goal was to demonstrate a method to reliably collect water flow and temperature data from every indoor water end use point, at the water heater and at the whole house meter in one second intervals when water was flowing. The overall success of the pilot phase study indicates that this technique can work. A complete study would be much longer in duration to capture differences between weekday, weekend, and seasonal variations. However, the pilot phase study did reveal shortcomings in many areas. These recommendations address those shortcomings and provide ways to improve the outcomes of the follow-on field study.

Because most hot water end use points, such as sinks and clothes washers, have an adjacent cold water end use point, adding cold water monitoring to the data acquisition system would require adding two additional data channels to the motes and installing another sensor set at each end use point. This effort would not require significant additional programming or field work. The value of additional information about cold water end uses compared to the incremental cost justify that this capability be included.

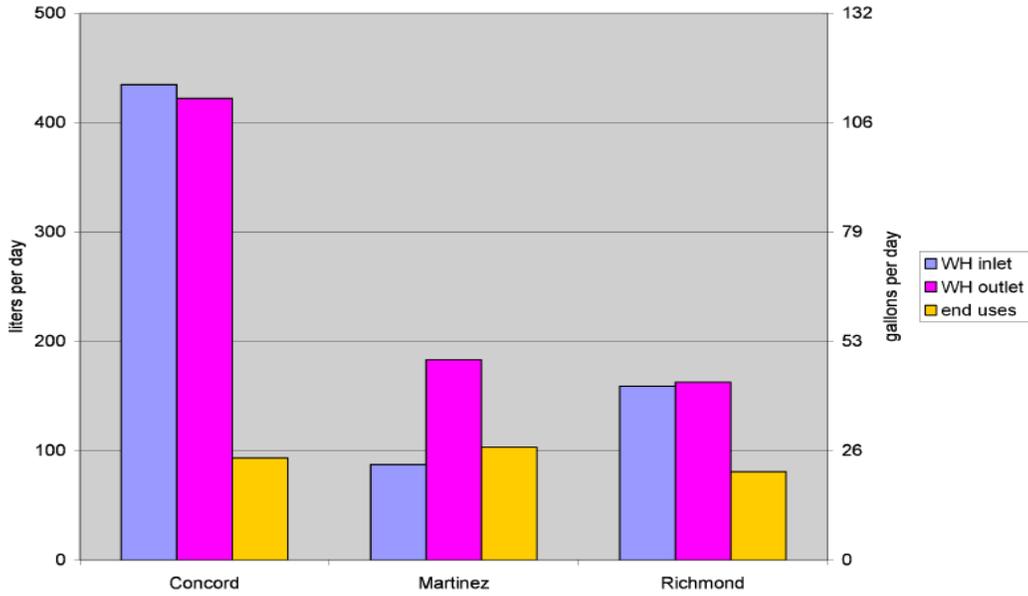
The recommendations are grouped into three broad categories; data collection, data transmission and data analysis. These groupings are analogous to the key hardware involved. The data collection corresponds to the sensors used to initially gather the flow and temperature data. The data transmission corresponds to the getting the data collected by the sensors onto the motes then wirelessly transmitted to the local processing and storage units on site and then transmitted to the central server. The data analysis means screening, cleaning and processing the monitored interval data from each house into results that can be used for policy recommendations. This analysis would occur on the central server.

## **Data Collection**

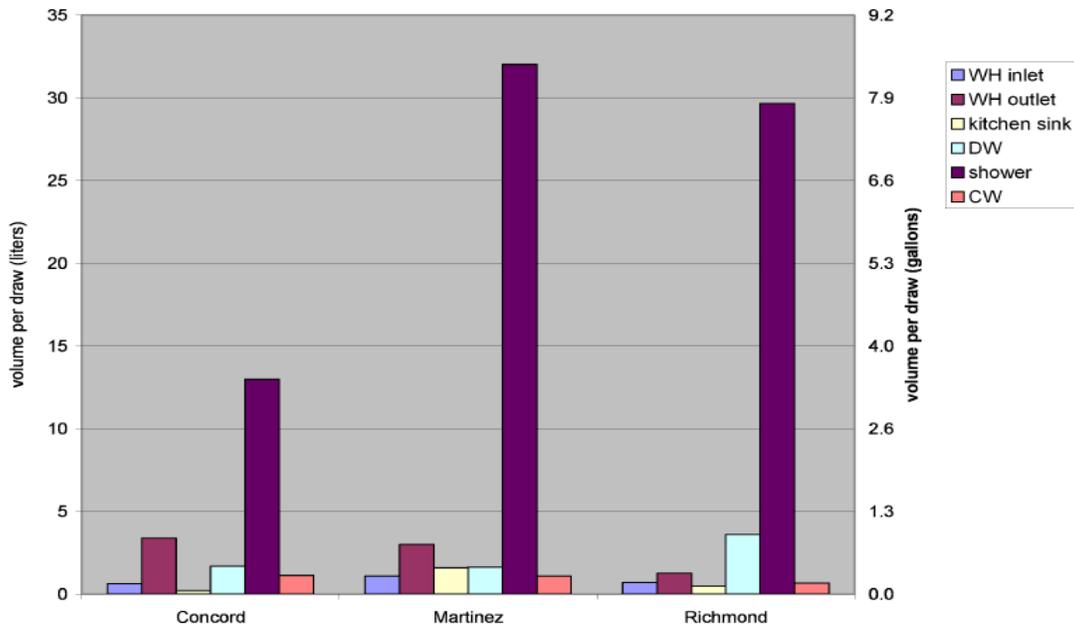
The sensors used for data collection in the pilot phase study were adequate. Temperature sensors with shorter response times and flow meters accurate to lower flow rates are recommended. Recommendations at this stage fall into areas of increasing the ease and robustness of installing system and improving the calibration of the flow meters.

The 10k ohm thermistor probes worked quite well at measuring water temperature in the pipes. The main shortcoming was the leads to connect the thermistors to the motes were fragile. The leads should be hardened and protected, perhaps by encasing them in plastic shrink tubing as they leave the probe. Another

option would be to install a jack on the thermistor. Then a separate wire could be run to the mote after all the sensors have been installed in the plumbing.



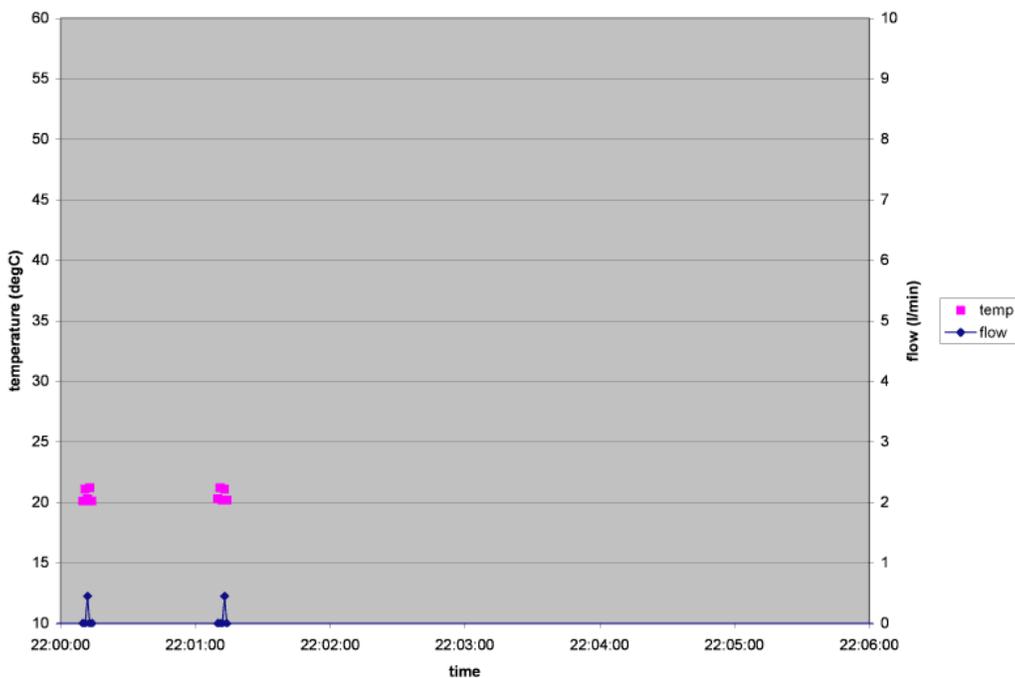
**Figure 6** Average daily hot-water use at the water heater and at end uses.



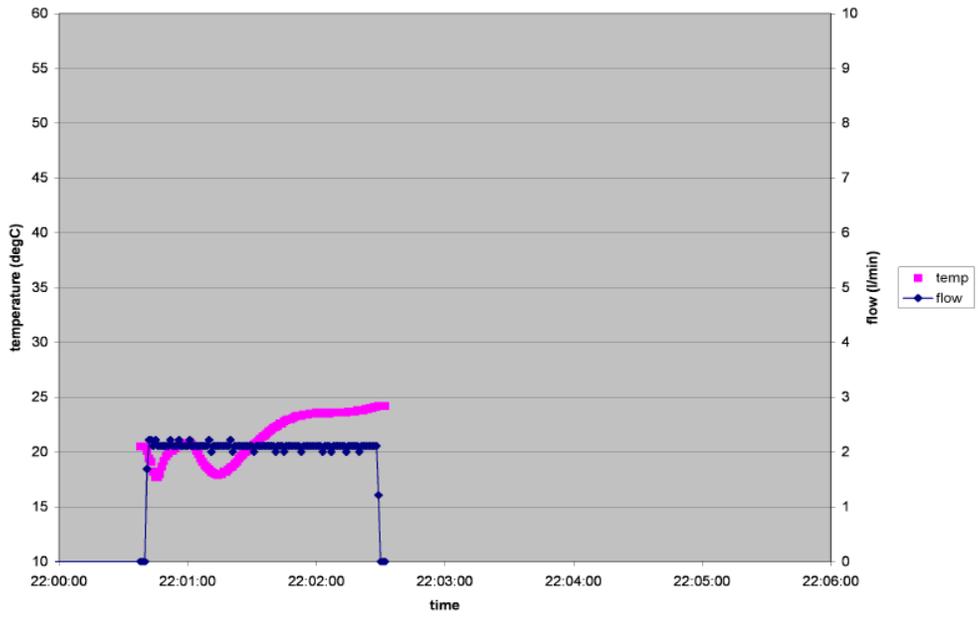
**Figure 7** Average Volumen per draw by end use.

The turbine flow meters with a Wiegand pickoff also worked quite well. The flow meters used at the water heater did not have as high resolution. This caused difficulties in some of the calculations. Either find higher resolution jet flow meters or consider using the turbine meters at the water heater as well.

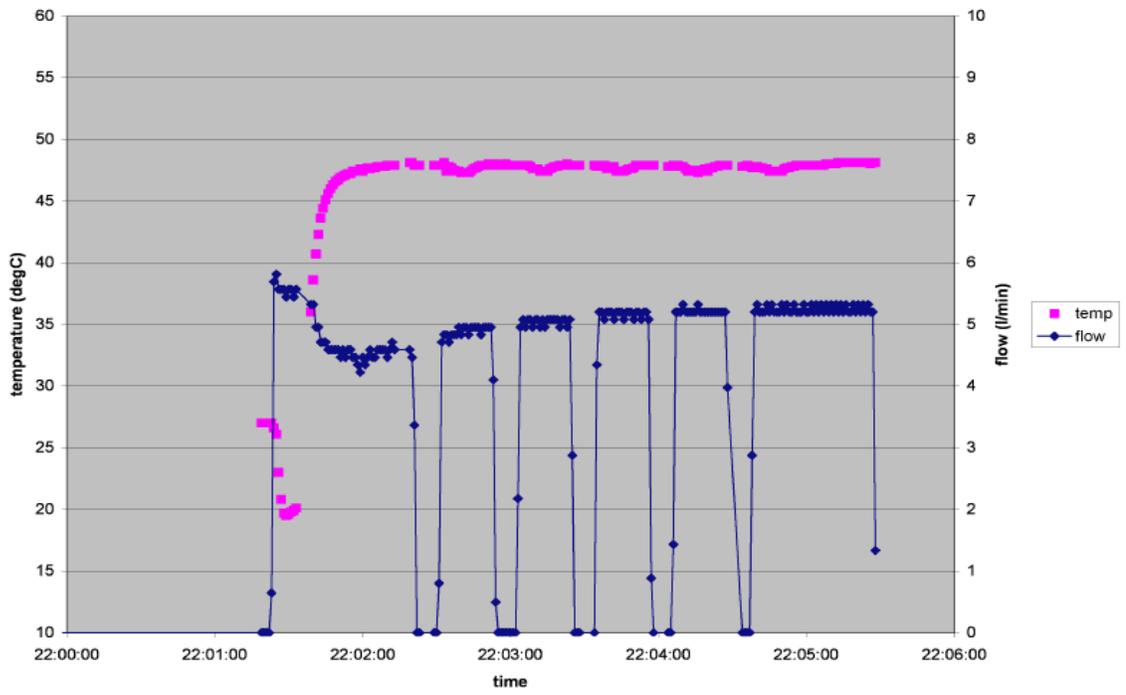
The anomalous average daily hot water use at the water heater, with different amounts of water apparently flowing into and out of the water heater over a day, could have been caused by back flow from the HWDS into the cold water system. Another possibility is that the two flow meters are not registering flow consistently or that data is being transmitted inconsistently. One way of determining if this is in fact happening would be to add pressure sensors at the inlet and outlet of the water heater. A differential pressure sensor across the water heater may be just as useful, but less expensive. This capability should be added to the data collection system. Pressure transducers that give a signal as a resistance would be capable of being read by the notes just as the thermistors are. This would preclude having special programs at the notes for this application.



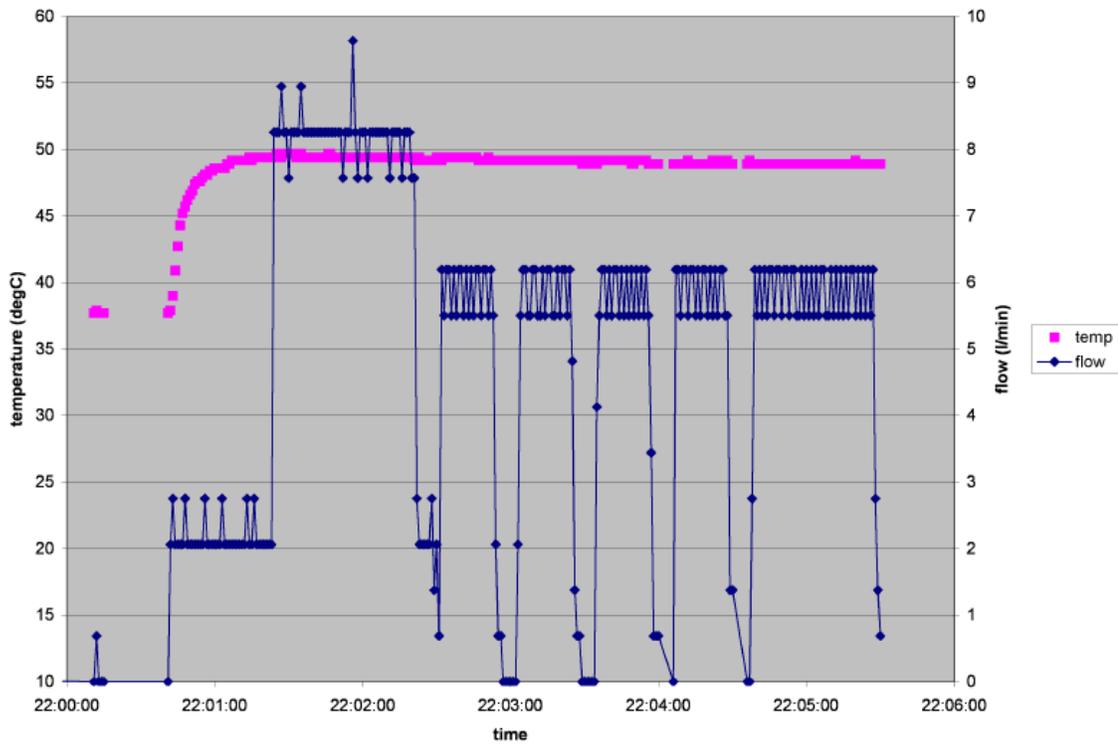
*Figure 8 Kitchen sink—Hot-water flow and temperature.*



*Figure 9 Dishwasher—Hot-water flow and temperature.*



*Figure 10 Clothes washer—Hot water flow and temperature.*

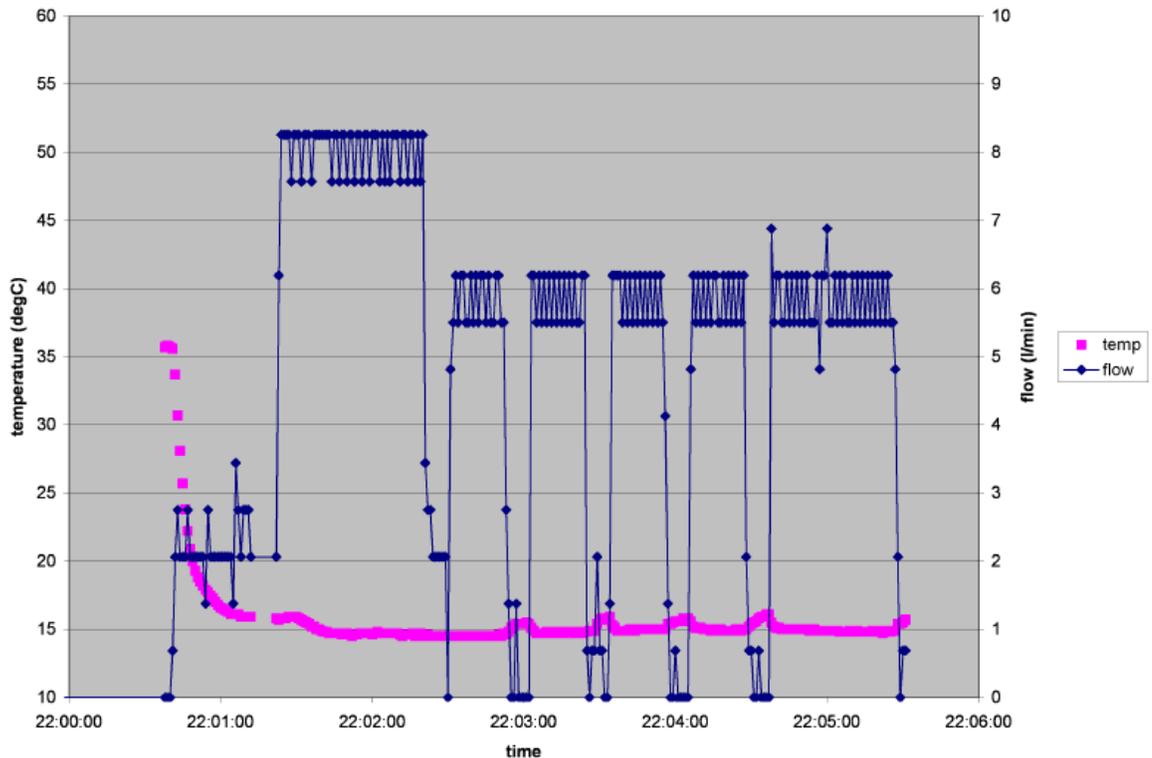


**Figure 11** Flow and temperature of water out of water heater.

Calibration of all the flow meters prior to data collection is important. This would be easiest to do at a dedicated installation in a lab. The set of sensors, motes, and local processing unit for each house should be tested before installation. A temporary plumbing loop should be set up with all the sensors installed in series. Water should be drawn through this loop at a graduated set of flow rates ranging from about 0.5 l/min up to 20 l/m (0.1 to 5.2 gpm). The time constant and calibration of the thermistors should be checked by a series approximately 5°C (9 °F) step changes in temperatures starting at 5°C (41 °F) going up to about 60°C (140 °F). A dedicated calibration bench using high quality sensors and a separate, automated data collection system based on laboratory grade data collection systems should be used.

## Data Transmission

The motes used in the pilot phase performed adequately but upgrading to take advantage of recent developments in wireless sensor network technology is strongly recommended. The motes used in this project were capable of operating as a mesh network, but in this case were implemented as a star network. Because of rapid pace of technological change, the available wireless sensor network hardware and topologies should be evaluated immediately prior to undertaking any work of this type. It is also important that the motes used in the field study be physically more robust than the early prototypes used in the pilot phase. Since they will be installed in relatively uncontrolled field conditions and may be subjected to occasional rough handling, the motes should be rugged enough to resist mishandling. The motes must be battery powered, as there is no guarantee of power nearby. It is important that changing batteries in the field be possible and not risk damaging the motes.



*Figure 12 Flow and temperature of water into water heater.*

**Table 5 Hot Water Distribution System Efficiencies for Selected Draws**

<b>End Use</b>	<b>Start time</b>	<b>End time</b>	<b>Efficiency</b>
Kitchen Sink	22:00:10	22:01:30	20.1%
Dishwasher	22:00:40	22:02:32	19.1%
Clothes Washer	22:01:21	22:05:28	90.5%

The mote platforms used in the pilot phase were able to detect the pulse signals from the Wiegand pickoff on the turbine flow meters. Pulses from the Wiegand pickoff are roughly triangular voltage spikes with peaks of about 3.3 V. The duration of the spike above 1.5V is about 10 microseconds. The maximum expected frequency in this application is approximately 300 Hz. Any new platform must be able to detect these pulses as well. It is expected that this will be standard in up-to-date motes.

In the pilot phase the pulses were summed for each second of flow. The number of pulses from the flow meter for each second was sent to the on site computer. A better strategy would be to keep a running total of the pulses and send the new total for each second. That would allow partial reconstruction of flow if some data is lost.

In the pilot phase the resistance of the thermistor was translated to temperature by the mote. To reduce the work load of the mote, this translation should be done on the server once the data gets there.

To reduce the number of transmissions and to increase redundancy in case of missed transmissions, as much data should be stored at the mote as possible. The exact amount of data to be stored at the mote will depend on the balance of energy and reliability between memory and transmission for the platform used in the field study. Sending packets with overlapping data, such that each recorded data point is send in two or more sequential packets, would provide additional redundancy to the transmission process.

From experience gained during the pilot phase, the software program on the motes should have features to assure robust operations, reliable signal transmission, and synchronization to within less than one second across the whole wireless sensor network. The algorithm that identifies draws could be improved to automatically fill in data if short gaps in measured flow are likely to have been caused by missing data rather than by stop in flow. The target for reliable data acquisition should be loss of less than one datum per million.

Given the intermittent nature of hot water use, it is important to have a regular signal from each mote that it is still operational. A lack of data received at the local processing unit could be due to the lack of any hot water draws at that end use, or it could be due to failure of the mote. A way to solve this is to transmit a “heartbeat” signal from the motes every 15 or 20 minutes. This heartbeat signal would be a basic report on the status of the mote. One crucial piece of data to include in the “heartbeat” signal is the remaining voltage on the mote’s battery. This will give an indication of the remaining life of the mote.

Another redundancy measurement would be to record data when the rate of temperature change is above a certain threshold. Triggering data monitoring on both flow and temperature rise or fall would provide some assurance that data will continue to be collected if flowmeters fail to measure low flow rates, or fail to work at all,

To assure that the motes are working as intended when installed, it is imperative to include some local indication of the status of the mote. One possible solution is to have LED indicators show the installer vital information such as whether the signal strength to and from the local computer is adequate, if the battery voltage is acceptable, whether data from the sensors is valid, and if time synchronization has been successful. To conserve energy in the mote battery, the LED indicators should be turned off after proper operation is assured. If the signal to the local computer is too weak, it may be necessary to add relay motes. This should be known at the time of installation so the relay motes can be added then.

The on-site processing unit should be a simple computer running a common open-source operating system. The computers used for pilot phase were salvaged PCs running a proprietary operating system. That operating system proved to be unreliable.

The local computer would store all data on-site as a local backup to the data that is passed to the central server each day.

The on-site processing units would be the connection between the local wireless sensor network and the Internet. Connections to the Internet would depend on the situation at the house being monitored. The possible network connection protocols could be cell phone modem (GSM), IEEE 802.11-wireless LAN standards (WiFi), or modems on land line telephone service (POTS) , whichever provides the easiest, most reliable service from that house. The motes should be IPv6 capable. This will allow remote access all the way to the motes for diagnostics and remote reprogramming without having to visit the site.

Each mote should be able to transmit data collected from four channels. For most motes this will be hot water flow, hot water temperature, cold water flow and cold water temperature. Each data set will be identified by a mote ID and a timestamp. The timestamps should be synchronized for all the motes to within a half second. The choice of how much data to store in the motes memory and how often to transmit data to the local computer will be made to maximize battery life. Understanding and minimizing the power use of the mote in all the modes of operation (data collection, data transmission, synchronization, initial start, data relaying, watching for data, wakeup cycles, sleep mode, etc) is important.

The wireless sensor network should be capable of operating as a mesh. This will allow additional 'relay' motes to be installed if the signal is too weak in any part of the network.

## **Data Analysis**

From experience with the pilot phase, the importance of having a mote designer and programmer on staff can not be stressed strongly enough. A field study should start with clear specifications of the necessary capabilities of the wireless sensor network.

The data coming in daily from each house should be checked, processed and entered into a database in an automated fashion. Each data point will be associated with a specific house, mote, and end use point. The date and time each data point was collected will also be noted. Because of the intermittent nature of hot water use combined with the indeterminacy of a wireless network, quality review of the data will be crucial. After being collected and stored, the raw interval data should be checked for consistency and plausibility. Initial diagnostic graphs should be reviewed daily by project staff. After the interval data has been checked, cleaned, and stored in another data table, it would be divided into draws. Summary information would be calculated and stored for each draw. Draws at the water heater and the whole house meter will be associated with end use draws. At this point the energy and water efficiency of the HWDS could be calculated for each draw. The actual efficiency of the HWDS depends on the plumbing configuration and the use of hot water. The timing and location of hot water draws also effects the efficiency of the HWDS. Further thought must be given to develop a representative overall rating for the HWDS.

Knowledge of hot water delivery delay time and wasted water is critical for this project. The time until hot water arrives will be calculated for each draw. The time response of the temperature sensors can cause a

significant temperature error, especially for short draws. Extra effort should be made to decrease the response time of the temperature sensors and improve the accuracy of the flow meters to lower flow rates. Alternate data analysis and presentation methods may help with some of these issues. Additionally, an uncertainty analysis should be carried out to provide estimates of the uncertainty in water and energy efficiency.

The vast amounts of data collected by such a field study mean that all the data processing and analysis procedures should be written as programs, scripts or macros and automated. To that end it vital to have an experienced database programmer as part of the staff of any project of this type.

Because of its reliability, widespread availability and lack of cost, open source software should be used for all stages possible in a project. This will allow widespread sharing and analysis of the data by parties not involved in the original project. Using open source software and providing copies of all programs and scripts would allow future extensions of the study. Use of open source software is also compatible with the public purpose goals of most funding sources

## **CONCLUSIONS**

From the experience gained in the pilot phase study, using wireless sensor network technology is clearly a feasible method for measuring water and gas flows and temperatures. It is a crucial technology to provide useful data for understanding the waste of energy and water in residential HWDS.

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