Energy Savings from a Comprehensive Multi-Family DHW Retrofit Program

Howard S. Reichmuth, PE and M. Sami Khawaja, Ph.D.
Quantec, LLC, Portland, OR

ABSTRACT

This paper documents the experimental results and energy savings estimate from an end-use and water metering study of a sample of 104 multi-family sites. These sites were treated with a comprehensive Domestic Hot Water (DHW) retrofit consisting of flow efficient 2.0 GPM showerheads, kitchen and bath aerators, tank thermostat setback to 130°F, and a tank wrap if necessary. These measurements were modeled by a regression model with variables for occupancy, setback degree, and delta flow at the primary showerhead. The model was used with actual measure installation records to extend the results of the study sample to the full participant population, in excess of 25,000 participants. The mean savings for the whole participant population at actual observed measure installation rates was 930 kWh per year per site.

Introduction

This analysis was designed to quantify the electricity and water savings resulting from a slate of water heating, space heating, and lighting measures targeted at saving domestic hot water and electricity in multi-family units. These savings were associated with a large utility program intended to serve multi-family customers.

Since the program's inception, 26,656 Oregon customers received conservation measures for their electric water heaters. Water heating measures included water tank wraps, pipe insulation, low-flow showerheads, and aerators. The thermostat settings were adjusted to 130° F, as necessary.

The measurement and verification approach was performed in two phases. In the first phase, electric water heat consumption and water savings were estimated using detailed metering of a representative sample of 104 multi-family home electric water heater tanks. Once data were retrieved from the sites, a multivariate regression model for estimating savings and extrapolating the results to the rest of the program was constructed.

The installed measures lowered water heating energy requirements through the following.

- Tank standby losses and fixed flow end-use loads were reduced by lowering water storage temperature.
- Tank standby losses were reduced by improving tank and pipe insulation.
- Water heating load was reduced by lowering showerhead flow rates.
- Water heating load was reduced by lowering the flow rates at kitchen and bath sink outlets.

At the outset, it was not clear that this program would have per site savings large enough to overcome the noise in water or electric billing data. Therefore, end-use metering on a representative sample was identified as the preferred method. However, an objective of the analysis was to establish water savings as well as electrical savings. This significantly complicates the metering task since, at each site, there were several water outlets to be metered. As a simplification, we opted to meter the water heater tank throughput flow. In general, the end-use water flows were at a temperature lower than the tank set point because of cold water mixed in at the point of use. Further complications arise because the quantity of mixed cold water is dependent on the tank set point temperature, which was changed between the pre- and post-measurement intervals. The water savings portion of this estimate required careful tuning of the metering methodology to account for tank set point changes.

The measurement and verification method reported here is intended to provide direct measurement of savings at a reasonable expense. It was designed to compliment a regulatory process that was stalled by various assumptions of showertime, user flow rates, etc. To be credible, measurement needed to get beyond the subjective assessment of showertime and flow setting and concentrate on an end-use measurement of pre- and post-total DHW energy.

Other studies have focussed on end-use energy, but none has been of a program with the same measures. One of the most rigorous prior studies (Warwick 1993) uses hourly annual DHW electrical end-use measurements. This study provides measurements of the seasonal demand impacts as well as the annual energy impacts. Unfortunately, some of the replacement showerheads used in this study were poorly matched to the sites and showed negative savings. This study underpredicts current practice showerhead savings. Another study that directly measured showerhead savings is an impact evaluation for Puget Sound Power and Light (SBW 1994). In this study, the end-use flows were measured by an elapsed flow meter at the point of use, and it gives some insight as to the distribution of hot water use by fixture type. Here again, the replacement showerheads were nominally 2.5 GPM, and the study probably underpredicted the savings associated with the current practice of 2.0 GPM replacement showerheads.

The more typical type of impact estimate involves an engineering estimate of savings from short- term site measurements and interview data. This approach was employed in a well known study of showerhead shavings for PG&E (Sumi, Miller & Proctor 1992). This study used a combination of telephone interviews and site flow and temperature measurements to synthesize a savings estimate, but this estimate did not directly measure the savings as in the Puget study. Another estimate of this type is found in an analysis of a showerhead program for SDG&E (Martin and Wiggins 1993). This study showed pre-retrofit flow rates in excess of 4 GPM.

Methodology

Data Collection

Water heater electrical and water consumption were measured at each site. The electrical consumption was recorded with a small data logger that recorded the cumulative run time while current ran through the water heater wire. This run-time measurement was then multiplied by the power draw for the water heater, which was recorded by actual measurement during the initial site visit. The installation procedure was to run the hot water until the water heater elements turned on, then measure the wattage using a clamp-on ammeter, such as the “Amp-probe.”

At each site, a water flow meter was installed on the cold inlet line to the water heater so that the amount of hot water used could be recorded along with kWh consumption.

At each site, staff recorded cold water temperatures from a cold water tap. One measurement per building was considered sufficient. Staff also recorded the hot water delivery temperature for each water heater. This was measured at a hot water tap near the water heater. Finally, staff verified the showerhead and faucet aerator flow rate reductions by measuring each shower pre- and post-retrofit using a "Micro Weir." This measurement confirmed the change in flow.

Two different test periods were analyzed. One period of approximately four weeks established the baseline consumption with existing equipment. The second period (also approximately four weeks) established consumption following the installations of low-flow showerheads, faucet aerators, and Water Heater Insulation Kits (WHIKs) and thermostat at rest. This testing required three site visits.

Data Collected

The specific site data collected were:

- Demographic and identification data (these included name, address, occupants, recent change of occupancy, dishwasher use, and clothes washer use).
- Hot water use by measuring water flow to and through the tank. These measurements were made using a water meter installed at the tank's cold water inlet.
- Measurements of the tank's inlet and outlet water temperatures. These were made by measuring the full hot and cold only temperatures at outlets nearest the tank after letting the water run for at least a minute.
- Water heater electric measurements. These were measured by attaching a magnetically induced elapsed time meter to the electric wires serving the water heater. These meters were actuated by the change in magnetic field in wires corresponding to the hot water heater elements' on and off states.
- Flow rate measurements (with a Micro Weir) on the original and replacement showerheads and faucets.

Data Cleaning and Normalization

Data cleaning a normalization proceeded in the following steps.

- Missing or inaccurate data caused by equipment failure were removed from the analysis. Data from periods of extended vacancy were also removed. To minimize variances in the results, we removed cases deemed to be anomalous using traditional statistical methods as well as common sense.
- Data loss from the initial sample of 104 cases varied by the variable of interest. For example, 72 sites had complete demographic and water usage data and no major periods of vacancies. These sites composed the core of this evaluation. The electrical runtime meters failed at all but 34 cases due to faulty installation procedures.
- To account for differences in the length of monitoring, consumption data were calculated as an average kWh per day for each site. Data for each site were normalized to average annual inlet temperature by corrections involving measured inlet temperatures.

For each site and each measurement period, amounts of standby and variable consumption were estimated using the following equation:

$$kWh/day_{Standby} = kWh/day_{total} - kWh/day_{variable}$$

where kWh/day$_{total}$ was the average kWh per day measured at the site during each measurement period. The kWh/day$_{variable}$ was computed as:

$$kWh/day_{variable} = (T_{out}-T_{measured})*(Gal/day)*\frac{8.33\ BTU/degFgal}{3412\ BTU/kWh}$$

Gal/day was the average water flow through the hot water tank at the site.

To adjust for seasonal changes in incoming water temperatures, the variable component of consumption for each site and each measurement period was adjusted using:

$$kWh/day_{Adjusted} = kWh/day_{Standby} + kWh/day_{variable} * \frac{T_{out}-T_{normal}}{T_{out}-T_{measured}}$$

where kWh/day$_{adjust}$ was the Daily kWh with average annual inlet water temperature, kWh/day$_{Standby}$ was the Amount of kWh/day consumption due to standby loss from the tank computed using the equation, kWh/day$_{variable}$ was the Variable amount of consumption, T_{out} was the Delivered hot water temperature measured at the site during each measurement period, T_{normal} was the Normal average annual cold water temperature.[1], and $T_{measured}$was the Measured cold water temperature at the site during each measurement period.

The adjustment for temperature applied only to the variable portion of the observed consumption. It was corrected only for the change in the inlet water temperature's difference between hot and cold.

Estimation of Annual Electric Savings

At each site, seasonally adjusted average annual variable savings were calculated as:

$$\Delta kWh/day_{adjusted_{variable}} = kWh_{variable_{pre}} * \frac{T_{out_{pre}} - T_{normal}}{T_{out_{pre}} - T_{measured_{pre}}} - kWh_{variable_{post}} * \frac{T_{out_{post}} - T_{normal}}{T_{out_{post}} - T_{measured_{post}}}$$

Installation of the water heater insulation and temperature reset primarily affected standby losses. Annual savings for insulation measures installed were separated as:

$$\Delta kWh_{insulaton} = (kWh/day_{standby_{pre}} - kWh/day_{standby_{post}}) * 365$$

Similarly, annual savings for water saving measures (mainly for showerheads) were computed by disaggregating the change in variable kWh into fixed flow and flow reduction savings. Daily savings associated with fixed flows were calculated as:

$$\Delta kWh/day_{fixed_{flow}} = FXT*(T_{out_{pre}} - T_{out_{post}}) * Gal/day * \frac{8.33\ BTU/degFgal}{3412\ BTU/kWh}$$

where FXT was the fraction of the hot water tank flow to fixed flows, such as dish and clothes washers. Calculations were based on the assumption that FXT, the fixed flow, was 35% of the pre-flow rate in gallons per day.

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1 This corresponded to the cold water temperature between 4/25/96 to 5/5/96, or the temperature taken on the first visit.

Annual savings associated with the flow reduction were calculated as:

$$\Delta kWh_{flow_{reduction}} = (\Delta kWh/day_{variable} - \Delta kWh/day_{fixed_{flow}}) * 365$$

Total annual site savings were calculated by adding these three savings components:

$$\Delta kWh_{total} = \Delta kWh_{insulation} + \Delta kWh_{fixed_{flow}} + \Delta kWh_{flow_{reduction}}$$

Estimation of Annual Water Savings

Data from 104 sites were screened for occupancy changes pre- to post-retrofit. All remaining sites with complete water measurements pre and post were selected as the water flow measurement set (72 sites). Some data reconstruction was necessary to fill missing dates and decimal point errors.

Water flow measurements were made with measurement intervals of 30 to 40 days. These flow measurements were normalized to gallons per day.

Water flow savings were not normalized for seasonal variability. As previous monitoring did not demonstrate significant seasonality for the amount of hot water consumed (ODE, 1987), programmatic results were the mean of estimated annual savings for all sites.

These water flow measurements were made at the tank and, therefore, were intermediate water flow measurements, as nonheated water consumption was also reduced. The measurements were consolidated with water inlet and outlet temperature measurements for use in estimating energy savings or water savings.

Gross flow savings were first corrected for tank outlet temperatures from pre- to post-period using the equation:

$$\Delta fgal/day_{corrected} = FXT * \left(1 - \frac{T_{out_{pre}} - T_{measured_{pre}}}{T_{out_{post}} - T_{measured_{post}}}\right) + f_1 * \frac{T_{out_{pre}} - T_{measured_{pre}}}{T_{out_{post}} - T_{measured_{post}}} - f_2$$

where FXT was the Fixed flow fraction assumed to be $0.35*f_1$, f_1 was the Pre-retrofit flow in gal/day, and f_2 was the Post-retrofit flow in gal/day.

The portion of the total corrected change in water use that is attributable to the program was calculated:

$$\Delta f_{fixture} = \left(\Delta fgal/day_{corrected} * \frac{T_{out_{post}} - T_{measured_{post}}}{T_{fixture} - T_{measured_{post}}}\right) * 365$$

where T fixture was the water delivery temperature at the fixture (assumed to be 105° F). (This was intended to be the weighted average of the shower and bath water temperatures. This was not measured, but rather assumed to be within the human comfort zone of 100°F to 110°F.)

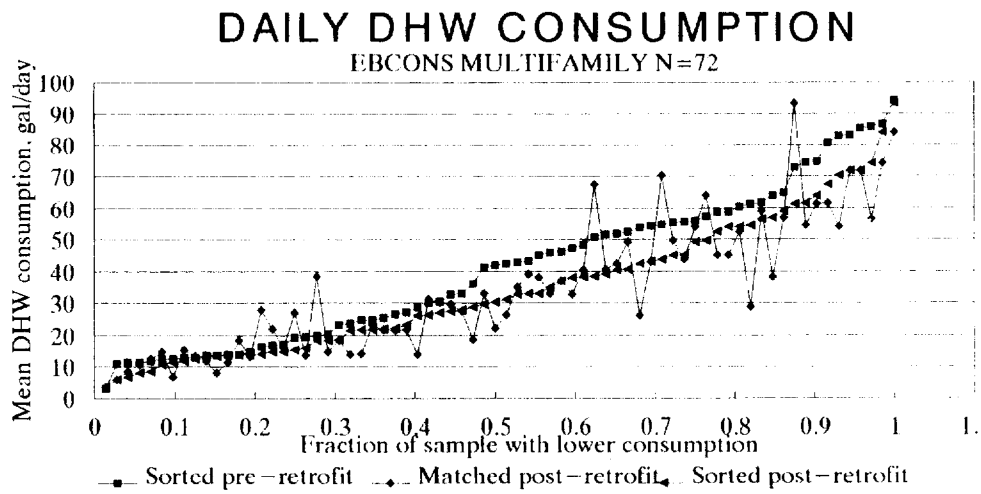
Analysis Results

The normalized seasonally corrected measurement data were reviewed and aggregated in Figures 1 through 3.

Figure 1 summarizes the water measurement results. The Daily DHW Consumption of Figure 1 normalized distribution of daily average water usage. There is a clear-cut reduction between the pre and post periods.

But note that this mean reduction is only 6.37 gallons per day. It is important to note that this tank flow reduction is at the tank discharge temperature, generally 140°F or higher. The flow reduction at the fixture is larger due to the mixture with cold water. After site-by-site corrections for pre- and post-tank discharge temperatures, the fixture flow reduction is estimated to be 16.9 gallons per day.

Figure 1. Water Flow at Tank



The mean Pre and Post usages and savings in gal/day are:

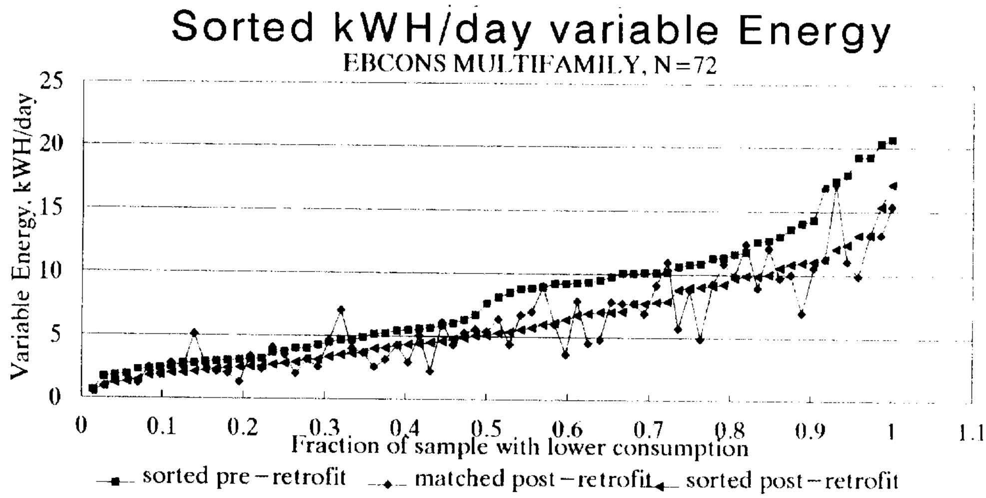
	PRE	POST	SAVINGS
Mean	40.99	34.61	6.37
Std Dev	23.55	20.80	10.41
+/- 90% confidence	4.57	4.03	2.02

Figure 2 summarizes the measurements of daily variable DHW energy use. In this figure, the average daily variable energy use is presented in the form of a normalized distribution showing the per site variable energy use varying from about 2 kWh/day to 20 kWh/day.

This is also a clean-cut shift in this distribution between pre- and post-retrofit showing a mean savings in variable energy use of 2.04 kWh per day.

Variable savings were disaggregated into two components: fixed flow and reduced flow savings. Fixed flow savings solely resulted from reducing the hot water temperature to water for end uses other than showerheads and aerator-installed faucets. Reduced flow savings were caused by a reduction of the volume of water used by the household. Both savings could be calculated using the previously cited equations with 35% of the water flow assumed to be going to fixed-flow appliances. Fixed-flow savings were estimated at 0.28 kWh/day, or 103 kWh annually, and reduced flow savings from installed showerheads and aerators were calculated at 1.75 kWh/day, or 640 kWh annually.

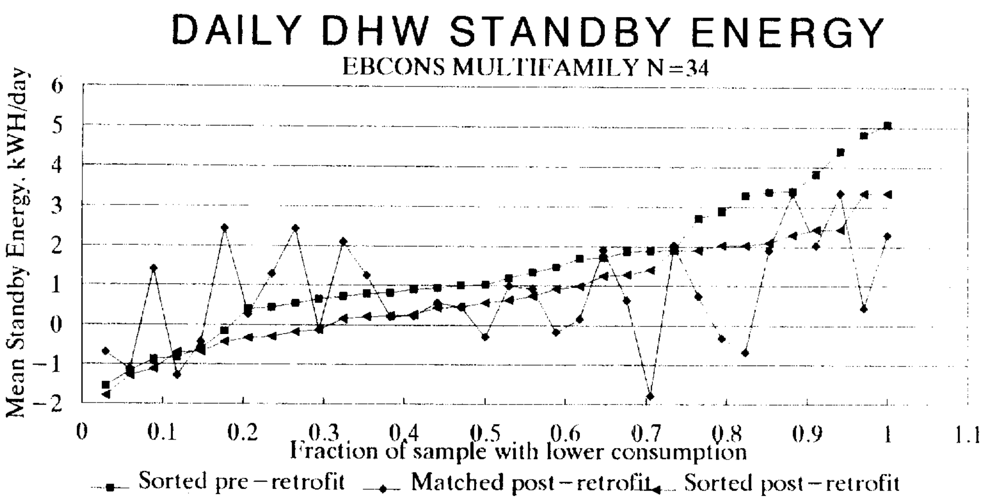
Figure 2. DHW Draw Energy



The mean kWH/day variable energy and savings are shown below in kWH/day:

	PRE	POST	SAVINGS
Mean	8.08	6.05	2.04
Std Dev	4.98	3.75	2.28
+/- 90% confidence	0.97	0.73	0.64

Figure 3. Tank Standby Energy



The Standby Energy and the standby energy savings are shown below in kWH/day:

	PRE	POST	SAVINGS
Mean	1.47	0.78	0.69
Std Dev	1.66	1.28	1.63
+/- 90% confidence	0.47	0.36	0.46

Figure 3 summarizes the measurements of daily standby energy use. This figure shows a normalized distribution of daily standby energy with daily standby energy varying from -1.5 kWh/day to 5 kWh/day. There is a clear shift in these distributions between the pre- and post-retrofit data showing a mean daily standby savings of 0.69 KWh/day.

Surprisingly, the distribution in Figure 3 shows negative standby savings for several sites, which is impossible for a tank maintained warmer than its surroundings. The implication for these anomalous cases is that more thermal energy emerged from the tank than the electrical energy input to the tank. The larger of these negative standby losses is too large to be attributed to measurement errors alone. It is more likely attributable to a process error that characterizes the inlet temperature to all sites in a building from a single measurement at the site nearest the water inlet to the building. The other sites in the building, on different floors and at least 100 feet from the primary water supply, are seeing inlet water preheated a few degrees by its passage through the building walls. However, this hypothesis was not verified. Assuming that this error was due to a persistent cause, common to both the pre- and post-measurement intervals, then the effect of the error will be minimal because the savings estimates are based on differences where the error will be cancelled out.

Total savings were estimated at 995 kWh per treated site. Measurements also showed average water savings of 6,169 gallons per year at each site, as in Table 1.

Table 1. Monitored Program Savings of the Analysis Sample

Electric Energy Savings	**kWh Per Day**	**Annual kWh**	**Percent of Total**
Fixed Flow Savings	0.28	103	10.4%
Flow Reduction Savings	1.75	640	64.3%
Standby Savings	0.69	252	25.4%
Total Electric Savings*	2.73	995	100%
Water Savings	**Gallons Per Day**	**Annual Gallons**	
Total Water Savings	16.9	6,169	100%

* Total savings were partitioned into the standby and flow-related components for the 34 sites with metered electric data. The average standby savings monitored in the 34-site sample was assumed to apply to the full 72-site study sample. Program standby savings formed the difference between pre- and post-period standby electricity consumption

Extrapolation of Findings to All Program Participants

Several multivariate regression models were constructed to extrapolate the estimated energy savings for the measurement sample of 104 sites to the full population of program participants. Essentially, the purpose of the regression model was to correct notable differences in the mean setback temperature and occupancy observed in the full population.

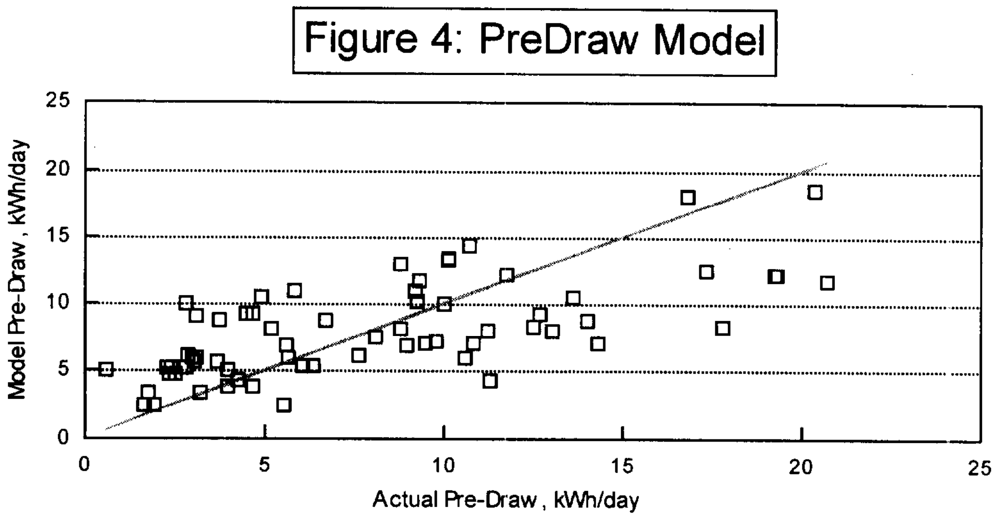
The model with the best fit to the measurements is executed in two steps:

(1) Step 1: Estimate Pre-Draw model. The Pre-Draw in kWh/day was estimated using:

$$PreDraw = \alpha + \beta_1\ Occupancy + \beta_2\ TempRise$$

where Pre-Draw was the pre-retrofit draw of the water heater in kWh/day, Occupancy was the number of occupants in the household, and TempRise was the difference between inlet and outlet water temperatures. (Model results were as follows: $\alpha = -5.56$, $\beta_1 = 3.05$, and $\beta_2 = 0.091$.)

Figure 4 displays the actual versus the regression-based estimate of Pre-Draw. Overall, the model provided a fairly good fit.

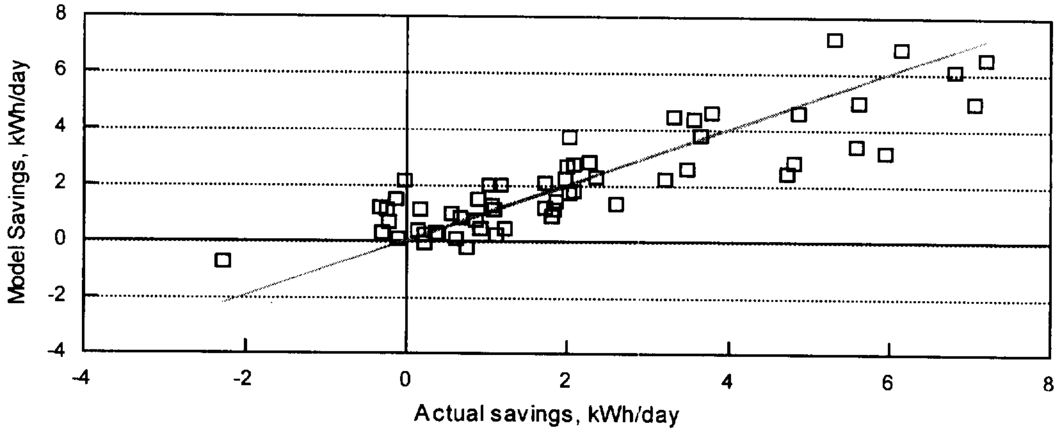


(2) **Step 2: Estimate Savings Model.** The average ΔkWh/day was estimated using:

$$\Delta kWh/day = \alpha + \beta_1\ PreDraw + \beta_2\ \Delta T + \beta_3\ Occupancy + \beta_4\ \Delta Flow$$

where ΔT was the temperature reduction (setback) and Δflow was the change in showerhead flow in gallons per minute. The model provided a good overall fit with an R^2 of 0.76. All variables, except Δflow, had significant t-tests (details provided in Appendix C). Figure 5 displays the estimated model (actual versus predicted saving values). (Model results were as follows: $\alpha = -0.47$, $\beta_1 = .040$, $\beta_2 = 0.0392$, $\beta_3 = -0.4188$, and $\beta_4 = 0.0058$.)

Figure 5: Savings Model



Inserting overall program averages into the regression resulted in savings of 2.43 kWh per day, or 889 kWh/year.[2]

The regression models only provided estimates of the variable savings and not the standby savings. The average standby savings of 252 kWh/day computed for the measurement sample was assumed to apply to the population. This was then added to the flow savings estimate of 889 to obtain a total of 1,141 kWh/day for the population. Table 2 displays a disaggregation for the population savings based on the percentage of savings distribution obtained from the study sample.

The population's average water savings were deemed to be equal to the sample's (6,169 annual gallons per participant).

Table 2. Program Population Savings by Type

Electric Energy Savings	Percent of Total	Annual Population kWh Savings
Fixed Flow Savings	10.4%	103
Flow Reduction Savings	64.3%	786
Standby Savings	25.4%	252
Total Water Heating Savings	100%	1,141
Water Savings		**Annual Gallons**
Total Water Savings	100%	6,169

2 Average Pre-Draw was estimated from Step 1 at 8.57 kWh/day, and average temperature setback of 10° F was estimated from the sample and assumed to apply to the population. A survey of program participants revealed that occupants averaged 2.31. As part of this project, laboratory tests were performed on the 104 showerheads replaced. These tests revealed that under typical water pressure conditions, the average water flow was 4.48 gpm. (This was slightly lower than the 4.8 gpm measured on-site for the regression sample.) With a final flow rate of 2 gpm, the Δflow for extrapolation was assumed to be 2.28 gpm.

Population savings per treated units still had to be adjusted for participating customers who did not receive all the program services. The total percentage installing each measure are shown in Table 3. The distribution of measures was obtained from the 3,000 randomly selected participants.[3]

As old showerheads were removed and low-flow showerheads were installed, persistence was not a concern. Water heater tank wraps were only removed in three cases (approximately 2% of respondents).

Adjusting the savings estimates to reflect the observed percentage of measures installed, the average per site annual savings from water measures was 787 kWh per participant (Table 3). Water savings were only associated with homes installing flow measures, and the adjusted savings were 4,855 gallons per year.

However, of the 26,656 program participants, only 92.7% had electric water heat and were eligible to receive the water heating measures. ***Adjusting the average savings for electric DHW produced average electric only savings of 730 kWh (787*0.927).***

Table 3. Calculation of Savings

Water Category	Measures	% Installing Measure	Avg Annual Population Savings (kWh)	Avg Adjusted Annual Savings Per Participant (kWh)
Fixed Flow	Temp Set Back	60.8%	103	63
Flow Reduction	Showerheads/Aerators	78.7%	786	619
Standby	Tank Wrap	41.6%	252	105
All Water Measures	All	NA	1,141	787
Water Savings (gallons per year)	Showerheads/Aerators	78.7%	6,169	4,855

Perspective on Results

Table 4 compares the results of this work with other recent work. Note that all of the studies employ slightly different experimental approaches and involve different program elements.

Table 4. Comparison of Gross Savings Estimates

Estimate (date)	Savings (kWH/yr)	Comments
Warwick 1993	374	♦ Field test with DHW end use measurements at 71 sites. Measured results of 545 kWH/yr/site were corrected for 80% of full installation and 86% electric DHW saturation to give 374 kWH/yr for comparison to other results. ♦ No kitchen or bath aerators were used, and there was not thermostat setback, and 14% of sites were retrofitted with a 2.5 GPM instead of a 2.0 GPM head. This result will understate the savings attributed to the PP&L single-family program. ♦ Test period was approximately 1 year pre/post. No explicit recognition of occupancy.

3 An auxiliary part of this impact evaluation consisted of a telephone survey to refine the population estimates for the occupancy and fuel type.

SDW 1995	939	◆ Syntheses based on survey data and test results from other studies, Puget, SCL. ◆ Survey data from this study provides the basic installation rate and electric/gas data used in subsequent studies. ◆ This study produces high results because of slightly longer shower duration and higher flow change than used by others. ◆ This study attempted to use bench flow data on approximately 1,000 participant showerheads. The high preflow rate from bench tests increases the sensitivity to the assumed throttle rates and shower times that came from small or unrelated samples.
Odoe/Opuc (1996) Unpublished	347	◆ Synthesis based on survey data and Delta T flow tests at showerhead. This is not an independent estimate of savings but a "common sense" check on prior savings estimates. ◆ Occupancy variations are implicit in shower duration assumptions.
PP&L (1997) Unpublished	513	◆ Synthesis based on survey data and negotiated input values. ◆ Calculation structured similarly to ODOE/OPUC estimate.
Current Work	434 – 529	◆ From field test and regression model for multifamily participants with same flow treatment. ◆ Adjusted for differences in single family and multifamily population and delivery mechanism. ◆ Data interval is approximately 1 month pre and post.

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