FACTORS INFLUENCING WATER HEATING ENERGY USE AND PEAK DEMAND IN A LARGE SCALE RESIDENTIAL MONITORING STUDY

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ABSTRACT

A load research project by the Florida Power Corporation (FPC) is monitoring 200 residences in Central Florida, collecting detailed end-use load data. The monitoring is being performed to better estimate the impact of FPC's load control program, as well as obtain improved appliance energy consumption indexes and load profiles. A portion of the monitoring measures water heater energy use and demand in each home on a 15-minute basis.

The paper summarizes the various impacts identified on water heating energy use and demand.

HOT WATER ELECTRIC DEMAND AND CONSUMPTION

The majority (153) of the water heating systems in the project were of the conventional electric resistance type. Seventeen of the monitored homes have natural gas or propane water heat and have no electric demand. These sites were eliminated from further analysis. Twenty eight (14%) of water heaters in the monitoring project have heat recovery units. There are also four operating solar water heating systems. There was also one tank-less water heater (Site 18). Eighty percent of water heaters were located in unconditioned spaces -- primarily in garages. Eighteen percent were located inside the conditioned zone.

Table 1 summarizes the recorded winter energy use and demand against selected water heating characteristics. Demand within the table is for the hour between 7 and 8 AM on January 5th, 1999, the coldest morning when no load control was applied.

The summary statistics on hot water heating showed that occupancy has the strongest influence on variation in energy consumption. Accordingly, within the table we also normalized water heating energy use and peak demand by number of household occupants. This showed that the apparent influence of tank size on peak demand resulted from the natural association between tank capacity and household size.

Beyond household characteristics, the water heating data revealed several important influences that may represent opportunities for FPC to meet its winter load control objectives.

- Heat Recovery Units (HRUs) showed elevated consumption during winter peak relative to electric resistance systems. This influence was unexpected.
- Despite a very small sample (n=4), solar water heaters showed large reductions in peak demand, and water heating energy.
- Hot water tanks with external insulation wraps and those located within the conditioned space showed markedly lower utility coincident peak demand.

Pipe insulation did not show up to be a statistically significant influence. We speculate that this may be due to the short plumbing runs. The issues of HRU performance and the impact of external tank insulation is examined in greater detail in the following sections.

Figure 1 shows a histogram of measured hot water energy use within the project sample.

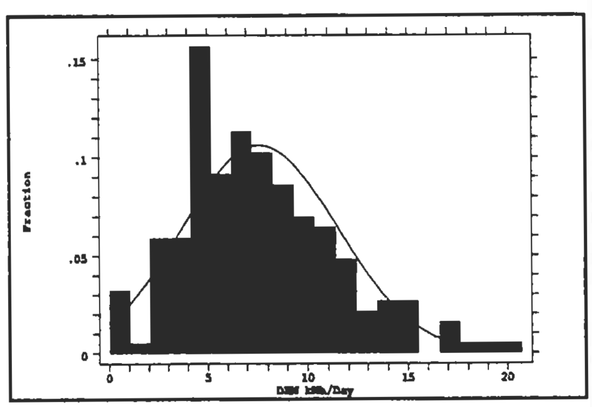

Figure 1. Histogram of daily hot water heat from January - March with a normal curve superimposed over the distribution.

Table 1
Effect of Selected Characteristics on Winter Electric Water Heating Energy Use and Demand

Characteristic	kWh Day	n	kW	n	kWhD/ Occupant	n	kW/ Occupant	n
Type								
Electric Resistance	7.69	154	0.718	129	3.14	151	0.293	126
HRU	8.34**	26	0.777**	20	3.48	24	0.324	19
Solar	3.11*	4	0.237*	4	1.97*	4	0.080*	4
Occupants?								
=1	4.36*	25	0.475*	23	NA	NA	NA	NA
=2	6.52	74	0.508	56	NA	NA	NA	NA
=3	9.48	25	0.750	21	NA	NA	NA	NA
=4	10.22	30	1.037	26	NA	NA	NA	NA
>4	10.37**	23	1.137**	22	NA	NA	NA	NA
Hot Water Timer?								
Yes	6.46*	27	0.653	19	3.01	26	0.316	18
No	7.89	156	0.722	134	3.20	152	0.289	130
Tank Size?								
<40 gal	5.768*	27	0.579	21	3.15	27	0.362	21
=40 gal	8.180	109	0.681	92	3.27	107	0.268	90
>40 gal	7.630	47	0.859**	40	2.93	44	0.313	37
Element Size?								
>4 kW	7.99	153	0.731	128	3.24	151	0.284	126
<4 kW >3 kW	6.62*	22	0.723	20	2.83	21	0.388	21
< 3 kW	4.76	8	0.233	8	2.45	6	0.051	3
Conditioned Space?								
Yes	7.99	30	0.524*	27	2.81*	29	0.220*	26
No	7.62	153	0.754	126	3.24	149	0.308	122
External Insulation?								
Yes	6.32*	27	0.501*	24	3.05	27	0.219*	24
No	7.92	156	0.753	129	3.19	151	0.307	124
Super Insulation?								
Yes	7.58	13	1.005	13	2.81	13	0.367	13
No	7.69	170	0.686	140	3.20	165	0.285	135
Pipe Insulation?								
Yes	7.91	39	0.761	39	3.25	36	0.317	30
No	7.62	144	0.700	120	3.15	142	0.286	118

* Significantly lower at > 90% level   ** Significantly greater at > 90% level

Seasonality of Water Heating Loads

Although water heating is not totally dominated by weather like space heating, these loads are still sensitive to temperature conditions.

Figure 2 shows how daily average hot water energy use varied in the sample by the daily average air temperature measured in the project.

Although, there is considerable scatter, a simple linear regression plotted explains 58% of the variation in the day-to-day hot water energy consumption. Moreover, including a dummy variable for weekends does nothing for the regression. DHW use is just slightly higher on weekends and although the demand profile differs this influence is not nearly as great as that of temperature.

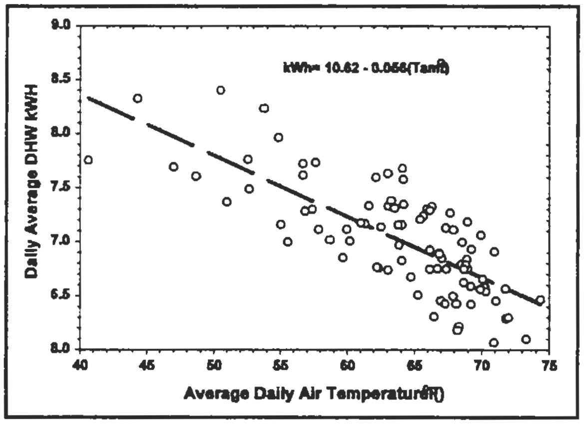

Figure 2. Impact of average air temperature on daily average DHW energy use during the winter of 1999.

Figure 3 shows the daily average 15-minute power DHW demand profile for the 183 sites with valid data for two days: January 5th the coldest non-load control day and July 20th, one of the warmest days analyzed. Average hot water energy consumption was 30% higher on the cold day based on variation in temperature. The graph shows that most 15-minute intervals had higher demand on the cold day.

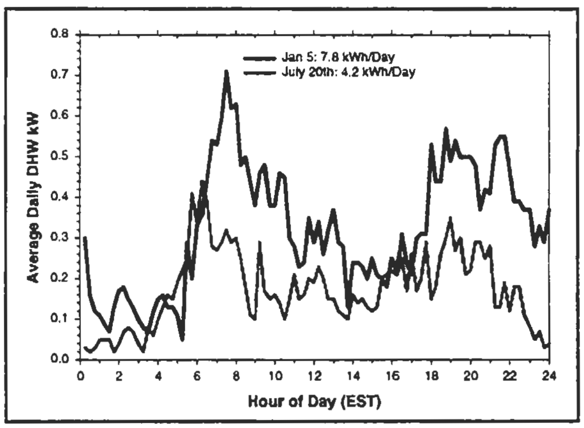

Figure 3. Water heating load profiles on two days with coldest and warmest conditions.

There are several reasons for this trend:

- Tap water temperatures vary seasonally by about 14 degrees in Central Florida. Although the annual inlet water temperature averages 74°F, this varies to a high of about 81°F in August to a low of 67°F in January as ground mains water piping is affected by weather conditions. Colder air temperatures are associated with colder inlet water temperatures which increase tank heating load to reach the set point. Figure 4 shows the measured mains water temperatures measured at FSEC's test laboratories.

- Greater standby losses. Colder air temperatures lead to greater standby losses for storage tank types – particularly those in garage locations.

- High hot water use. Colder air temperatures lead to greater hot water use as household members take longer showers to warm up and use more hot water within the mix to achieve the preferred water temperature. This has been observed in previous monitoring projects where residential hot water consumption was measured to increase by 15-20% from summer to winter (Merrigan and Parker, 1991; Brecker and Stogsdill, 1990).

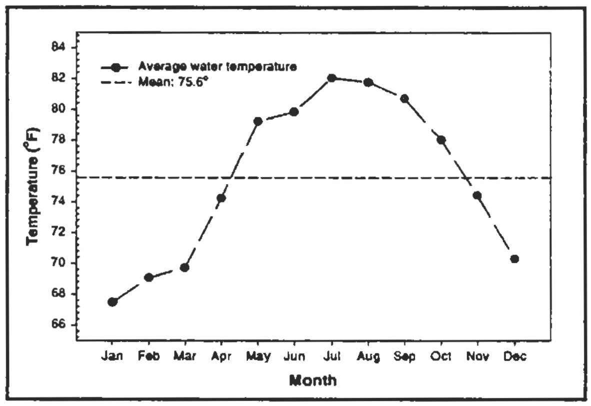

Figure 4. Monthly mains water temperatures measured at FSEC's test laboratory.

The seasonal nature of DHW loads was not unexpected. A previous large scale monitoring project in the Pacific Northwest showed similar trends (Pratt et al., 1989). One study in the literature on load control does acknowledge the seasonality of LM impacts for water heating (Haeri and Gervais, 1992) and suggests that load profiling or time temperature matrix (TTM) may be superior for assessment.

The current FPC TTMs for water heat vary by month, which captures some of the seasonal variation described. However, we found it necessary to produce hot water TTMs which respond to temperature – particularly to capture the elevated DHW demand on the most extreme winter days. This is important since the need for load control is highest on these days. For example, the average January DHW demand between 7 and 8 AM is only 0.54 kW. However, during hours when the temperature was near 32°F at 8 AM the typical demand was 0.75 kW – a 39% increase in load.

Eligibility of water heating systems for load control is not affected by whether the homeowners have non-standard water heating systems. Many households have heat recovery units and several have solar water heaters or heat pumps water heaters. Thus, the total sample of all-electric water heaters are included in the time of day estimate of water heater load for computing the regression based load profiles. Sites with natural gas or propane water heat were not included. Estimates are contained in Table 2 for the period between January and July, 1999. The estimates in Table 2 have the form:

$$kW_{dhw} = A_j + B_j(T)$$

Where:

A_j = Non-temperature responsive component of water heat demand (kW)

B_j = Temperature coefficient for DHW electric demand in hour "j" (kW/°F)

T = Outdoor ambient air temperature (°F)

Table 2
FPC Residential Monitoring Project
Water Heater Hourly Demand (kW)
Values (n = 186)

Hour	Constant (A)	B_1
1	0.225	- 0.00146
2	0.143	-0.00076
3	0.159	-0.00117
4	0.153	-0.00109
5	0.182	-0.001185
6	0.377	-0.002433
7	0.855	-0.006017
8	0.977	-0.006959
9	0.762	-0.004058
10	0.547	-0.001738
11	0.508	-0.001714
12	0.533	-0.002499
13	0.561	-0.003222
14	0.535	-0.003450
15	0.465	-0.002641
16	0.432	-0.002316
17	0.512	-0.002744
18	0.571	-0.002662
19	0.779	-0.004387
20	0.743	-0.004064
21	0.720	-0.004771
22	0.706	-0.004976
23	0.462	-0.002283
24	0.340	-0.001502

The profiles in Figure 5 show the described seasonality in water heater energy demand. The water heating loads are somewhat lower than commonly supposed. Part of this is due to the advent of low hot water using appliances and showerheads (EPRI, 1997). Another part of the low consumption comes from occupancy; some homes (e.g. Site 50) were unoccupied during much of the study while others (e.g. Site 22) turned off the water heater breaker when away from home for extended periods.

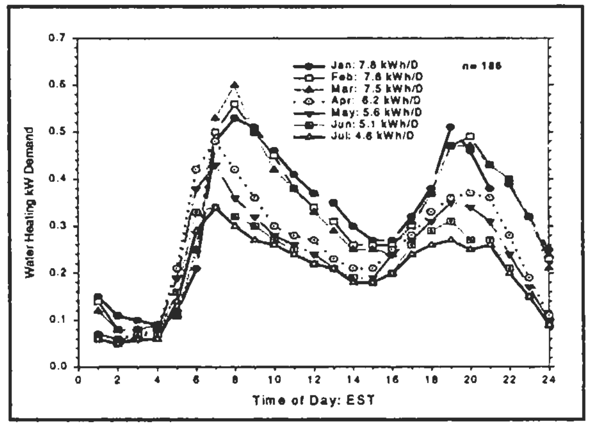

Figure 5. Measured average DHW load profiles by month.

Water heating loads are greatest during the colder months. April clearly shows the shift in timing of water heating load imposed by Daylight Savings Time. The later spring and summer months show progressively lower water heating loads.

Water Heating System Type

We examined how water heating system type influenced electric demand and energy use. Some 14% of the sample (28 sites; 26 sites with valid data) had heat recovery units which scavenge heat from the air conditioning system to heat water. Four homes had operating solar water heating systems. Figures 6 and 7suggest some interesting facets concerning the operation of these water heating systems.

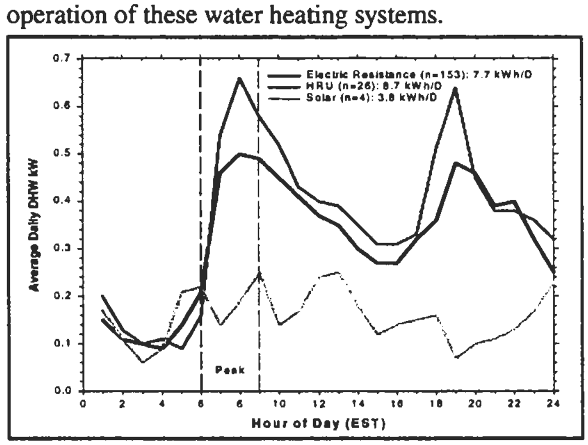

Figure 6. Measured January DHW load profiles by system type.

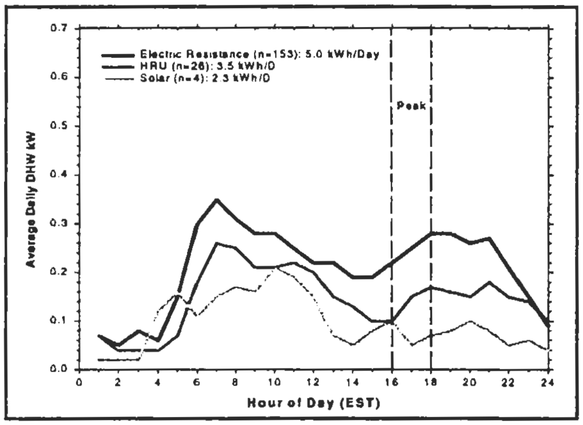

Figure 7. Measured July DHW load profiles by system type.

As expected, the average demand profile in July shows that HRU water heaters used about 30% less electricity than the electric resistance group. Demand was also lower in all hours. Secondly, solar water heating systems show even better relative performance and demand reductions during the peak hour, although the sample size is small.

Heat Recovery Systems

First, the HRU systems used more energy and produced more electric demand for water heating in winter than their electric resistance counterparts. The demand difference between the two systems from 7 - 8 AM during January was approximately 160 Watts or about a 32% increase in utility winter coincident morning demand. Further the difference was statistically significant at a 99% confidence level.

Daily water heating energy use was also 1.0 kWh greater in the homes with HRUs (13% greater). One explanation for this difference is that HRU owners use more hot water during winter on the mistaken belief that "hot water is free." Elevated hot water consumption associated with HRU users has been observed in another comparative project in which HRUs and electric resistance systems were metered (Merrigan, 1983). However, physical explanations for the poor performance are more compelling:

- Total or partial failure of the circulation pump. On site evaluation showed that most of the units suspected of improper operation had failed pumps. This is likely due to air lock in the exchanger loop leading to premature failure of the pump. Unfortunately, there is no feedback device to inform the consumer that the circulation pump is operating properly.

- The HRU pump is normally activated by a switch which circulates water through the system when the refrigerant temperature exceeds 135°F. One problem occurs when the circulation switch is activated when refrigerant discharge temperature during heating operation is just above the activation temperature. This is possible since the heat pump compressor discharge temperature in heating mode is approximately 100°F above the ambient temperature (a common method of checking a heat pump's refrigerant charge). The tank element may be activated by the resulting circulation which is not high enough to gather useful heat.

- During winter operation when cooling is required, the HRU exchange loop may be activated, but since cooling needs are satisfied quickly in winter (often within 5 minutes) the loop shuts down almost as soon as the refrigerant temperature reaches the critical level. This results in decreased efficiency as the HRU loop circulates heated water from the storage tank which increases thermal losses. Meanwhile, the heat exchange loop has insufficient time to capture any useful heat and the resistance element may be activated.

Summer data shows the advantage expected for these systems. Here, the electric resistance water heaters use about 5 kWh per day as opposed to 3.5 kWh for the HRU systems. The demand reduction from 4 - 5 PM is only 100 Watts, however. The savings in daily water heating energy use is 1.5 kWh or approximately a 30% reduction in water heating energy.

Annually, however, the advantage of HRU systems may be marginal, both for the utility and for the consumer. Over the period from January - July, the average consumption for electric resistance water heating systems was 6.36 kWh/day as opposed to 6.23 kWh/Day for the HRU systems (suggesting annual DHW energy use of 2320 and 2270 kWh, respectively). Although water heating energy is saved during summer, this is nearly offset by increased consumption in winter. Thus, the apparent annual energy reduction for the consumer is only a few percent.

Unfortunately, the reduction in demand during the summer utility coincident peak is less than the increase in the winter coincident peak and the annual reduction in hot water energy use is very small for the consumer. Although it seems likely that a number of the systems are not functioning properly, the added capital expense may be difficult to justify. From a utility load control perspective, it seems very desirable to load manage HRU sites to gain full advantage from them – particularly given their elevated winter demand.

One obvious influence on HRU performance is the selected hot water thermostat setting. Since condenser heat temperature may be no higher than 140°F, those systems with high settings may perform poorly. Unfortunately hot water set temperature was not collected in the audit, although an exit collection of this information may be useful.

Diagnostic Evaluation of HRU Performance

Given the problems identified with HRU performance, we examined each of the sites possessing these systems to determine which sites appeared to be functioning properly. This was done by plotting daily hot water energy consumption against daily air conditioning energy consumption from January - July of 1999. Generally, one should expect to see hot water electricity consumption decline as greater air conditioning provides auxiliary heat for hot water. This trend is clearly evident in Figure 8, which shows the two values plotted for the HRU at Site #10.

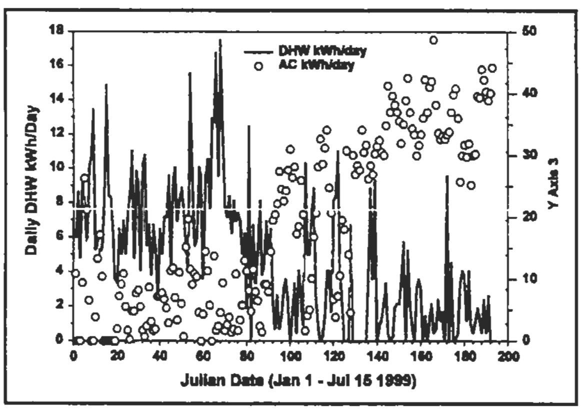

Figure 8. Measured daily hot water and air conditioning energy use at Site 10. Note that as air conditioning increases around Julian day 90 (March 31st), recorded water heating electricity use falls dramatically. The green line is the measured average daily hot water energy use from January - March which AC requirements are low.

We found that 12 of the evaluated HRUs fell into this category of proper function. Unfortunately, there was a group of 10 households with HRUs that showed no discernable impact of increased air conditioning use lowering hot water electric consumption. An example of this problem is shown in Figure 9.

Three other HRU sites could not be classified due to little air conditioning use or vacancy.

We returned to the homes that had an HRU to verify our conclusions regarding the operation of the HRUs. A surprising 27% were disconnected either electrically or at the refrigerant lines. In the future, field auditors are being trained to observe the HRU closely to attempt to determine if the unit is disconnected or functioning properly. Twenty-three percent of the HRUs' pumps were inoperable or air-locked. The remaining 50% of the HRUs were operating properly as our cursory evaluation of the daily air conditioning and water heating consumption indicated.

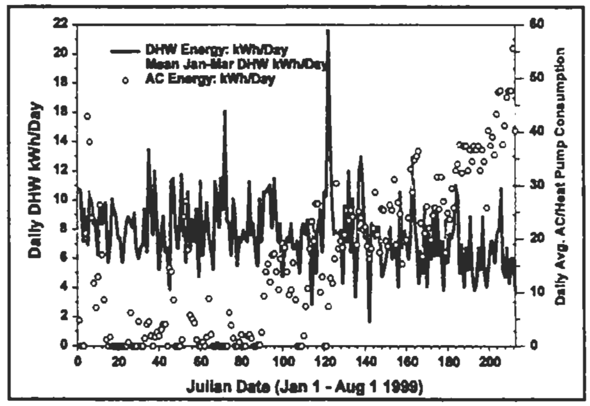

Figure 9. Measured daily hot water and air conditioning energy use at Site 2. Note that although air conditioning increases around Julian day 90 (March 31st), recorded water heating electricity use shows little reduction. Moreover, high sustained levels of air conditioning since after day 152 (June 1st) show little impact of DHW energy.

Solar Water Heaters

There are four operating solar water heating systems in the project. Although a small sample, they showed large reductions in coincident demand as well as energy. The reduction in seven month energy use was 52% against electric resistance systems. Utility peak coincident reductions were approximately 0.35 kW in winter and 0.10 kW in summer.

Impact of DHW Element Size on Peak Demand

Down sizing of hot water tank elements is an idea which seems as if it could impact how water system peak demand. Unfortunately, the project data showed the impact is very small.

We used data for January 5th of 1999 (the coldest non-load managed day) and examined how the recorded water heater electric demand varied depending on the water heater element size (reliably available in the data set from the maximum recorded kW over the entire season). The lack of impact has to do with the diversity of water heating with respect to hourly demand. Simply put, so few of the water heaters are on at the same time, that although changing an element to a smaller one will reduce the demand for that single household at the time they use hot water, it will not have much effect on the overall population since hot water draws are nearly randomly distributed over the hour-long window of interest.

For the 153 non-gas sites which had valid data from the project that morning, the average water heater electric demand was 0.713 kW. The average electric water heater element size was 4.424 kW. This implies a diversity of 16% overall – most water heaters were only on a small fraction of the time. A frequency distribution shows that over 45% of water heaters were not on during that hour in spite of no load control (Figure 10). Many of these systems were likely on the hour before or after the hour examined (related to diversity of occupant showers, schedules, absence, etc.).

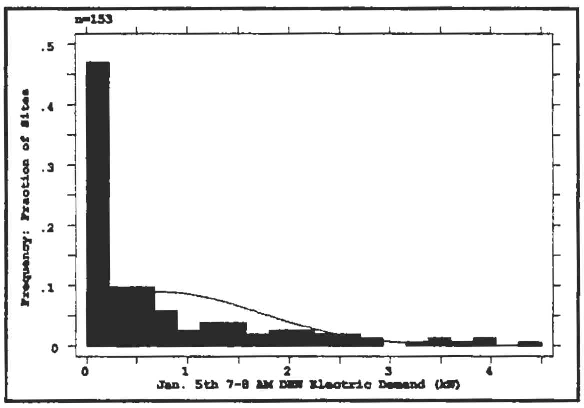

Figure 10. Histogram of DHW electrical demand at 7-8 AM on January 5th, 1999. Note that fully 45% of tanks require no power during this hour.

To look into element size, we segmented the data into two groups: one with the element size was between 4 and 5 kW and another where the element size was between 3 and 4 kW. We then compared the hourly average demand in the two groups:

Element Size	Avg Element Size	Diversified kW	n
4-5 kW	4.586	0.7266	122
3-4 kW	3.558	0.7229	20

Although the sample sizes are very different, the diversified kW is nearly identical and a statistical t-test of means showed no meaningful difference.

A second estimate utilizes a duty cycle approach with the histogram in Figure 10. Limiting element size to 3.5 kW would only impact the five water heating systems (3% of the population) whose average hourly demand was greater than that value. Applying the duty cycle method estimates an average population demand reduction of only 15 watts.

As a final check, we censured the sample to only those systems that had some power draw on the DHW circuit during the peak hour:

Element Size	Avg Element Size	Diversified kW	n
4-5 kW	4.596	1.248	71
3-4 kW	3.558	1.205	12

The 40 watt difference is in the expected direction, but still shows no statistical significance (t=0.134) with a small sample size. A non-parametric test of medians (Wilcoxon Rank Sum Test) showed that while there may be a small difference from a smaller element size, the difference is very small. The duty cycle assessment above is likely the most accurate estimate. In any case, our findings are in line with other investigations of the same question (Colliver et al., 1988).

Hot Water Tank Wrap

Evidence emerges from the analysis that exterior tank wraps show large impacts on the measured hot water tank electrical demand, yet a much lower influence on energy use. This can be exploited to help control winter peak demand.

Theory/Laboratory Measurements

Detail measurements of hot water tank standby losses were performed in an environmental chamber by Ek at the Bonneville Power Administration (BPA) (1984). BPA showed that electric storage tanks of the modern type have a heat loss coefficient of approximately 0.93 W/°F. When an R-11 exterior tank wrap is added, the loss coefficient drops to approximately 0.65 W/°F. With a hot water tank temperature of 130°F and a surrounding temperature of 40°F (e.g. an unconditioned garage or utility room), the average reduction in tank standby losses from an exterior tank wrap should amount to approximately 25 W.

Field Estimates

There were 26 sites within the project sample which included external tank insulation wraps. The average demand of these sites on January 5th between 7 and 8 AM when the outdoor temperature was 37°F was 0.501 kW. This compares to 0.753 kW in the sample without an external insulation wrap. The difference 0.252 kW is significant at the 90% level but is very different from the value predicted by laboratory measurement. This may be because changing the heat loss rate of the tank significantly alters diversity so elements are not immediately activated when hot water is drawn. Further, the differences still remain after controlling for household occupancy – the largest carrier of variation within water heating data. If solar water heating systems and tanks located within the conditioned space are excluded from the control sample, the estimated savings increases further (0.40 kW peak reduction). Finally, a photographic review of the hot water tank wraps in the monitoring project show that at least half of the applications are marginal (partial tank wraps, insulation missing, etc.). A utility sponsored program should be able to choose effective insulation kits (e.g. Consumer Reports, 1981) and lead to effective applications. Thus, hot water tank wraps look to have a large potential impact on winter peak hot water power demand if costs of installations are low.

The measured reduction to annual water heating energy would entail some energy savings. Within the winter data, the average reduction in daily water heating energy consumption was 1.6 kWh/day. Average daily savings over a year will be no more than half this value, since ambient tank temperature differences are much lower at other times. Regardless, the measure would have the simple benefit of reducing customer energy costs in a modest fashion while significantly impacting winter coincident peak demand from non-load controlled customers.

CONCLUSIONS

The project has identified a number of influences on water heater electric demand that are not commonly described. This includes the pronounced seasonality of water heating demand load shapes as well as the time of day influence on loads. The project has also revealed that recent weather conditions have a strong influence on water heating demand beyond the normally recognized seasonal effect. A number of additional impacts were identified:

- Heat recovery units (HRUs) and solar water heaters were associated with lower demand in summer months. However, HRU systems were also found to increase winter peak demand on average. A diagnostic evaluation showed that only about 50% of installed HRU systems were operating properly. Failed circulation pumps were identified as the most common reason for poor performance.

- Water heater element size was not found to statistically impact winter peak demand.

- An exterior hot water tank insulation wrap was found to be associated with reduced winter peak demand.

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