Factors Influencing Water Heating Energy Use and Peak Demand in a Large Scale Residential Monitoring Study

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ABSTRACT

A utility load research project has monitored 171 residences in Central Florida. Water heater electricity use and demand was measured to evaluate various factors impacting water heating energy efficiency.

Introduction

A load research project by a large utility has monitored 171 residences in Central Florida, collecting detailed electricity end-use load data. In each home, 15-minute electric demand data is obtained on total electric power, space heating, cooling, water heating, dryers, cooking and pool energy use. Interior and exterior temperatures were also recorded. This is similar to other detailed end-use data monitored in the United States: the ELCAP project in the Pacific Northwest (Pratt et al., 1989) and the PG&E Appliance Metering Project (Brodsky and McNicoll, 1987). However these data are of a more recent vintage and from a cooling dominated climate.

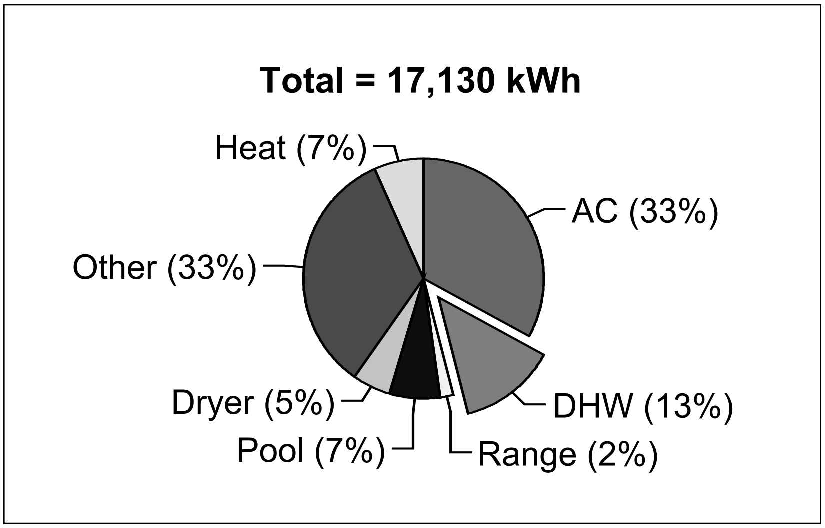
The homes represent a statistically drawn sample using end-use metering to identify ways in which the residential peak load might be reduced within its load management as well as to obtain improved appliance energy consumption indexes and load profiles. The conditioned floor area of the homes averaged 146 m^2, with very detailed data taken on many characteristics associated with each site. The extent of the collected data (100 million data points) provides an extremely rich data source for evaluating energy efficiency improvement potential of homes in hot climates. This paper highlights influences and findings for the water heating end use.

Total and Other Electricity Consumption

Total electricity use was metered in all homes by monitoring incoming electrical service. Major end-uses were also recorded in each home on a 15-minute basis. These included space heating, cooling, water heating and either pool, dryer or range. We derived “other” electricity consumption by subtracting all the sub-metered end uses from total.

The total average annual electrical loads in the sample was 17,130 kWh. Other electricity consumption is large in magnitude within the homes. For homes where there was no non-metered pool, dryer or range, “other” averaged 5,730 kWh/year. Space cooling averaged average 5,650 kWh, space heating 1,070 kWh and domestic water heating (DHW) 2,240 kWh. Water heating averaged 13% of total electricity use. Figure 1 top of the next column shows the relative percentage of each measured end-use.

Figure 1. Measured Electricity Consumption by End-Use (N = 171)



Note that "other" is larger than any individually identified loads save for cooling. Although non-metered refrigeration comprises an estimated 1700 - 2500 kilowatt hours/year and lighting another estimated 1,500 kWh of this total, this still leaves a large quantity of electricity consumption that is not easily categorized.

Hot Water Electric Demand and Consumption

The majority (150) of the water heating systems in the project were of the conventional electric resistance storage type. Eighteen of the monitored homes have natural gas or propane water heat and have no electric demand. Twenty (10%) of water heaters in the monitoring project have connected heat recovery units. There are also four operating solar water heating systems. There is also one tank-less water heater. Eighty percent of water heaters were located in unconditioned spaces – primarily in garages. The rest were located inside the conditioned zone.

The water heating loads in Florida are 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 seasonal (warmer water temperatures) and occupancy.

As expected, the summary statistics on hot water heating showed that occupancy has the strongest influence on variation in energy consumption. Average annual electricity consumption for electric resistance systems averaged 6.37 kWh/day or 2,325 kWh/year. Consumption varied considerably by occupancy. Average number of occupants was 2.8, but two occupants was the most common household number. Figure 2 shows a variable width box plot of DHW electricity use against household occupants. The centerline is the median, the box top and bottom are the inner quartile range and width is proportional to sample size. Beyond household characteristics, the water heating data revealed that hot water tanks with external insulation wraps and those located within the conditioned space showed lower winter utility coincident peak demand (16% and 10% respectively). Figure 3 shows a histogram of the frequency distribution of measured hot water energy use.

Figure 2. Box Plot of Daily DHW Electricity Variation with Household Size

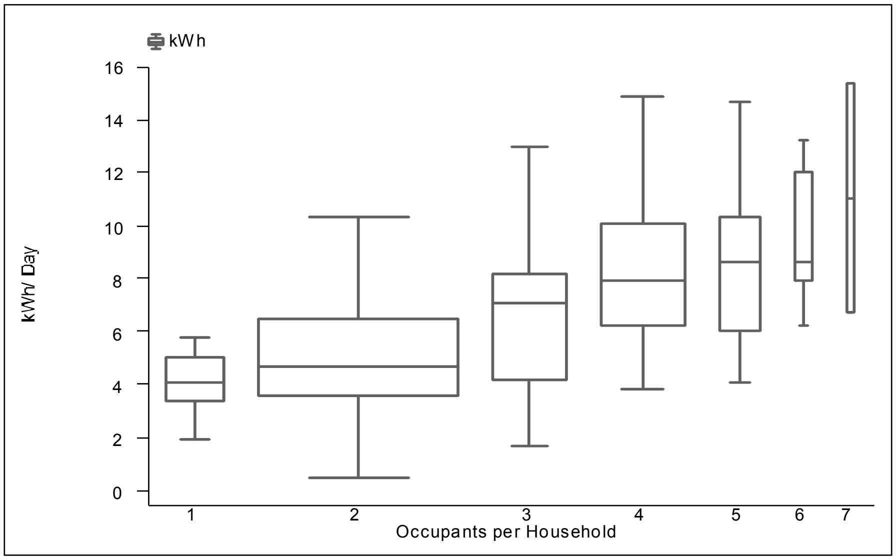
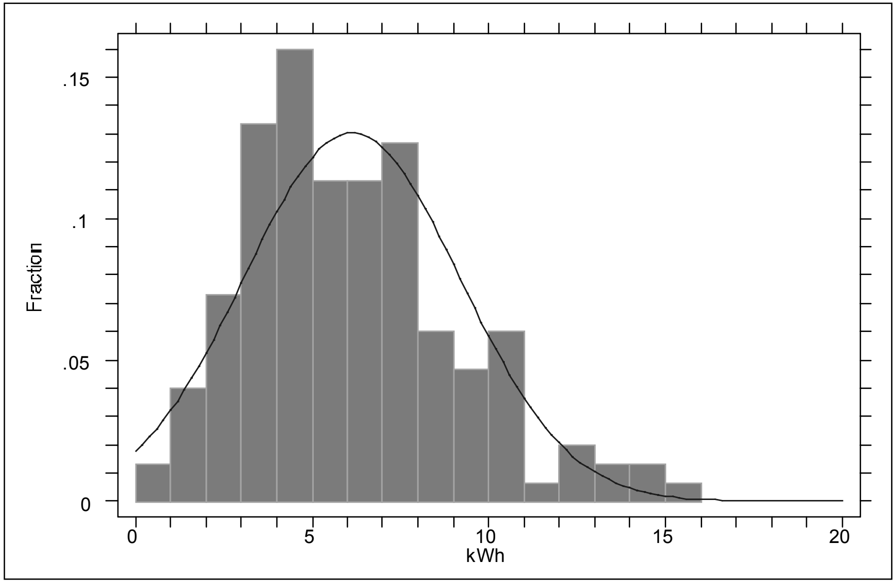


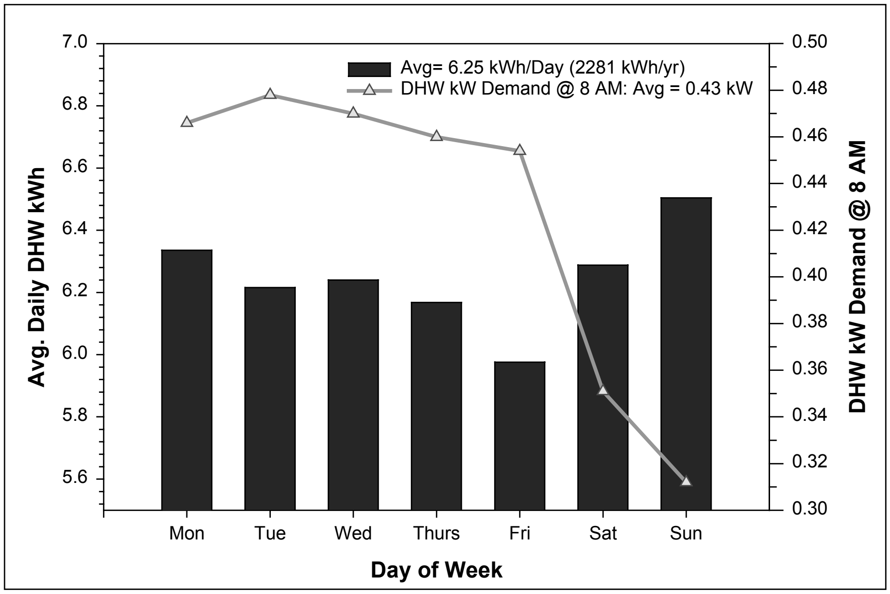
Figure 3. Histogram of Daily Hot Water Electricity



Day of Week Variation in DHW Loads

Figure 4 shows the impact of the day of the week on average measured water heating electrical loads over the entire year of 1999. The bars show the impact of day of the week on daily average consumption (kWh/day) while the connected superimposed line shows the impact on the average DHW electrical load between 7 and 8 AM in the morning. This is important since it is generally the time of the daily winter morning system peak demand.

Figure 4. DHW Use and Peak Demand by Day of Week

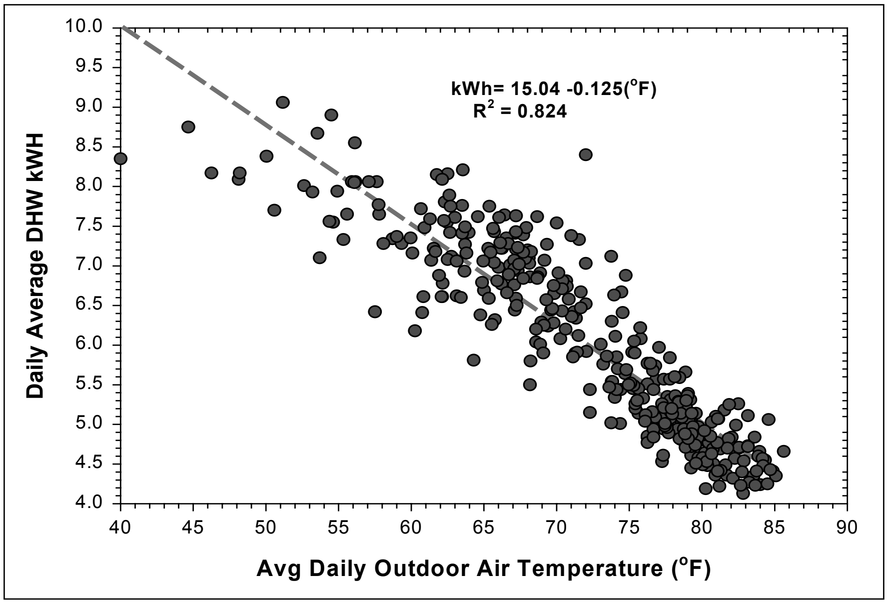


Weekday water heating energy use is similar. Mondays have the greatest consumption and Friday are a bit lower, perhaps due to early weekends. However, weekend days clearly show increased hot water energy consumption (greater occupancy), but generally peaking at a later time of day (households sleeping in). Sunday shows the greatest difference in consumption and 8 AM peak demand from the other days of the week.

Seasonality of Water Heating Loads

Although water heating is not totally dominated by weather like space heating and cooling, these loads are still sensitive to temperature conditions. Figure 5 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 little for the regression. DHW use is just slightly higher on weekends and the demand profile differs, however this is not nearly as great as that of temperature.

Figure 5. Impact of Air Temperature on Daily DHW Use



There are several reasons for this influence:

- Tap water temperatures vary seasonally by about 8°C in Central Florida as seen in Figure 6. Although the annual inlet water temperature averages 24°C, this varies to a high of about 27.2°C in September to a low of 19.4°C in February as ground water piping is affected by weather conditions.
- 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 themselves 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 increased by 15-20% from summer to winter (Merrigan and Parker, 1991; Brecker and Stogsdill, 1990).

The summer data shows even greater weather related impact for water heating. As shown in Figure 7, the 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.

Figure 6. Variation of Mains Water Temperature over the Year in Central Florida

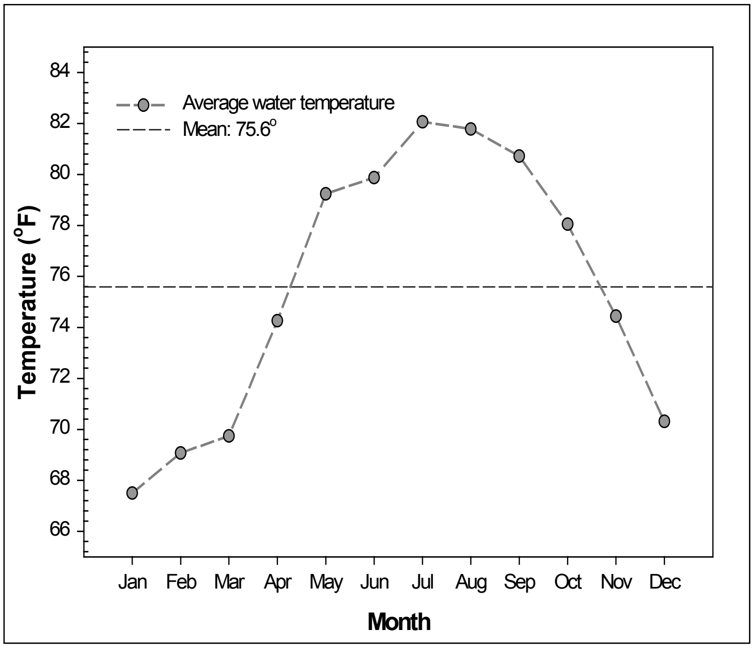
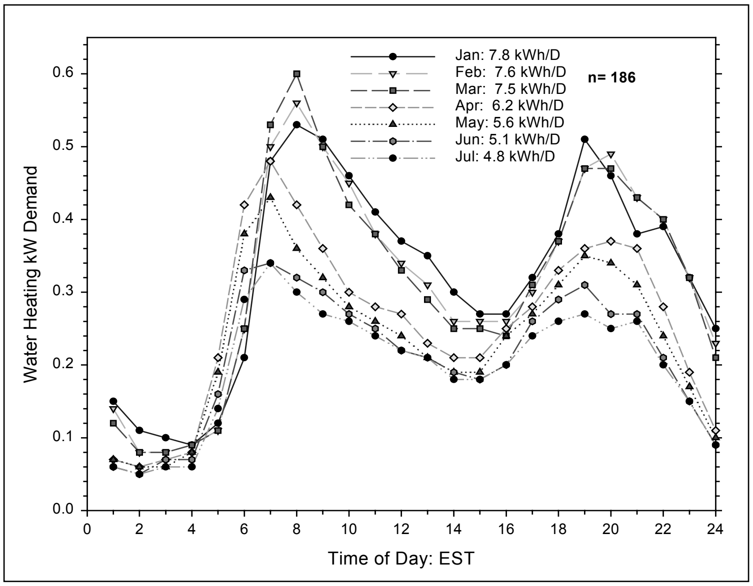


Figure 7. Measured DHW Load Profiles by Month



Water Heating System Type

We examined how water heating system type influenced electric demand and energy use. Some 10% of the sample had heat recovery units which scavenge heat from the air conditioning system to heat hot water. Four homes had operating solar water heating systems. Figures 8 and 9 displays performance characteristics of these water heating systems in both winter and summer.

Figure 8. January DHW Load Profiles by System Type

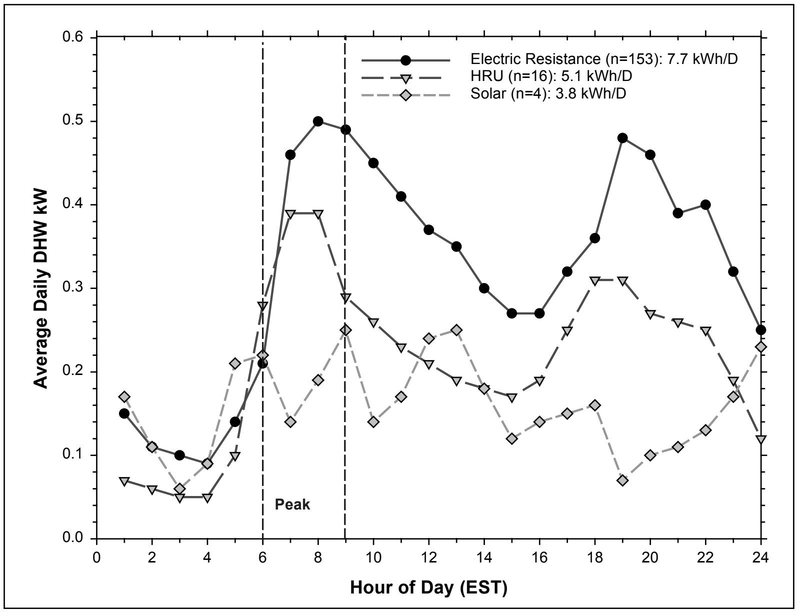
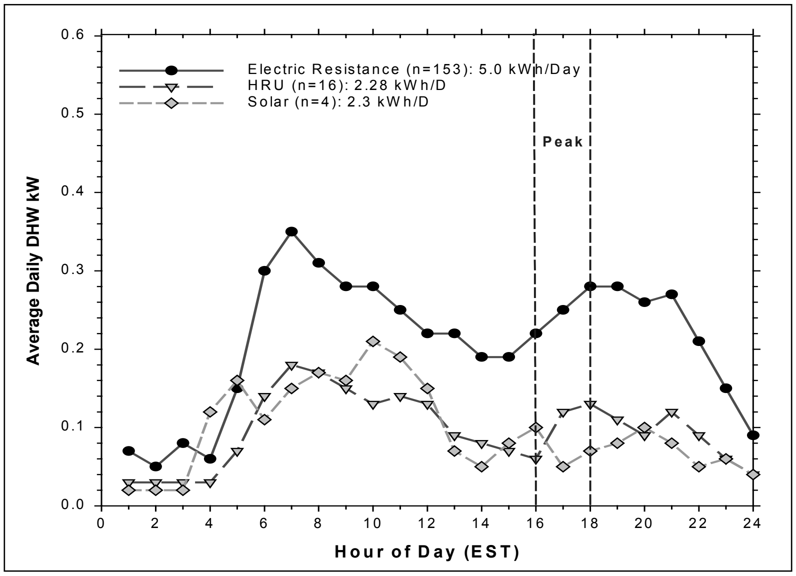


Figure 9. July DHW Load Profiles by System Type



As expected, the average demand profile in July shows that HRU water heater used less electricity than the electric resistance group in all hours. The electric resistance water heaters use about 5 kWh per day as opposed to 2.3 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 2.7 kWh or approximately a 54% reduction in water heating energy.

The situation for winter months shows less advantage. First, the HRU systems used 34% less energy. They also reduce electric demand slightly in winter compared to their electric resistance counterparts. The demand difference between the two systems from 7-8 AM during January was approximately 110 Watts or about a 22% reduction in utility winter coincident morning demand.

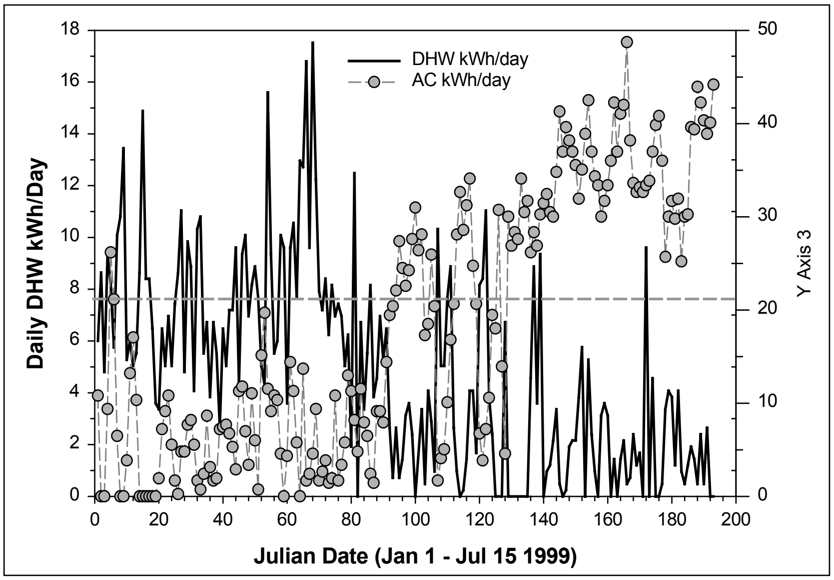
Over the one-year period, the average consumption for electric resistance water heating systems was 6.37 kWh/day as opposed to 4.63 kWh/Day for the HRU systems (suggesting annual DHW energy use of 2,325 and 1,689 kWh, respectively). This is a similar level of performance that was observed in another comparative project in which HRUs and electric resistance systems were metered (Merrigan, 1983).

The four operating solar water heating systems showed large reductions in demand as well as energy. The reduction in annual energy use was 61% against electric resistance systems. This indicated an annual average electrical reduction of 1,420 kWh/year. Peak reductions were approximately 0.31 kW in winter and 0.14 kW in summer.

Diagnostic Evaluation of HRU Performance

Based on site-by-site scrutiny of performance data we suspected that a number of HRUs were not functioning well. Given the problems identified with HRU performance in a previous study (Merrigan, 1983), we examined each of the sites possessing these systems to determine which sites were 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 10, which shows the two values plotted for the HRU at Site #10. Note that as air conditioning increases around Julian day 90 (March 31st), recorded water heating electricity use falls dramatically. The dark line is the measured average daily hot water energy use from January – March which AC requirements are low.

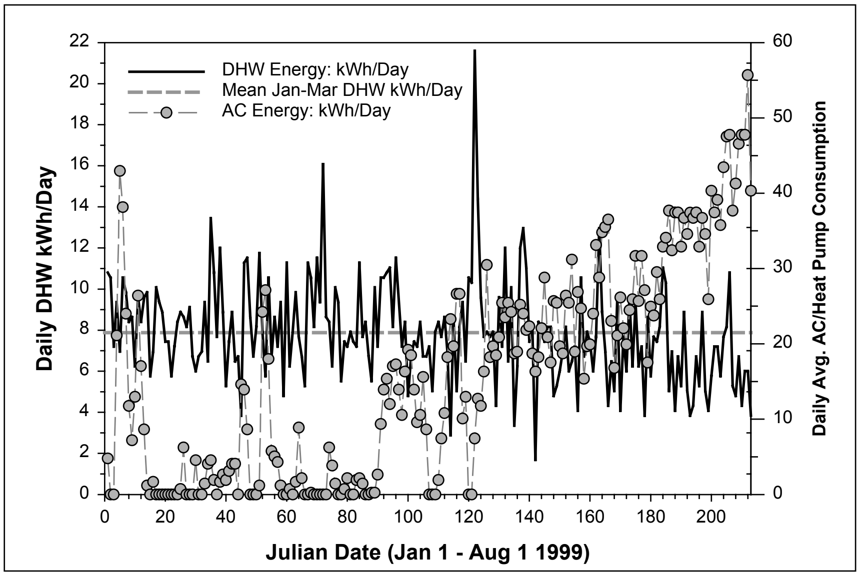
Figure 10. Measured Daily Hot Water and Air Conditioning Energy Use at Site 10



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. A number of these were later found to be disconnected, which was not evident in the immediate audit. An example of this problem is shown in Figure 11. 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.

Each of 20 differing systems were evaluated in the field. Of these, some 14 or 70% were found to be functional. The other six (30%) were not working. In all but one case this came from failed circulation pumps (often due to air lock). The other case occurred when the AC contractor installing a new system neglected to reconnect the refrigerant lines to the HRU. The fact that 30% of systems were not operating underscores the need for some type of feedback mechanism to provide consumers with certain information as to whether HRUs are functional.[1]

Figure 11. Measured Daily Hot Water and Air Conditioning Energy Use at Site 2



Of the total sample electric resistance systems used 6.51 kWh per day. For the 20 HRU systems the numbers shows 5.21 kWh – an apparent energy reduction of 20%. However, when confining the HRUs solely to those 14 systems which were determined to be functional, the average consumption was 4.95 kWh per day – a savings of 24%.

Due to its unbiased nature, the statistical sample is likely the best estimate of relative HRU performance. Estimating the number for the "pure" statistical sample showed the 133 electric resistance systems using 6.37 kWh/day against 4.63 kWh for the 14 HRU systems (a 27% reduction). However, confining the analysis to the nine working systems revealed a 34% annual energy reduction (4.19 kWh/day). Further, although this group did not show any reduction to water heating demand on the winter peak morning (January 5th) it did cut demand on August 30th during the peak hour between 5 and 6 PM. During this time, the

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[1] This could be as simple as a differential temperature measurement on the supply and return water lines which would signal (a red light perhaps) if the supply line was not warmer than the return line when the compressor was operating. Such a device would alert consumers to the need for service.

systems with functional HRUs had recorded diversified water heating electrical demand of only 50 Watts against the average of 170 watts for conventional resistance systems. This represents a 120 Watt load reduction (70%).

One interesting finding came from examination of systems with disconnected HRUs. These exist at six sites (5 within the pure sample). These sites showed a tendency towards elevated water heater energy use possibly due to losses from unused piping. Although the sample is too small to make conclusions, the ten sites with disconnected HRUs or those not working showed an average consumption of 7.0 kWh/day – over 10% higher than for other standard resistance systems.

In any case, these results suggest that properly functioning HRUs can reduce water heater electric demand and save consumers energy. However, our evaluation indicated that about one third of installed HRU systems were not properly operating. Successful operation is not obvious, and auditors should be trained to use a simple temperature test to determine if HRUs are functional.

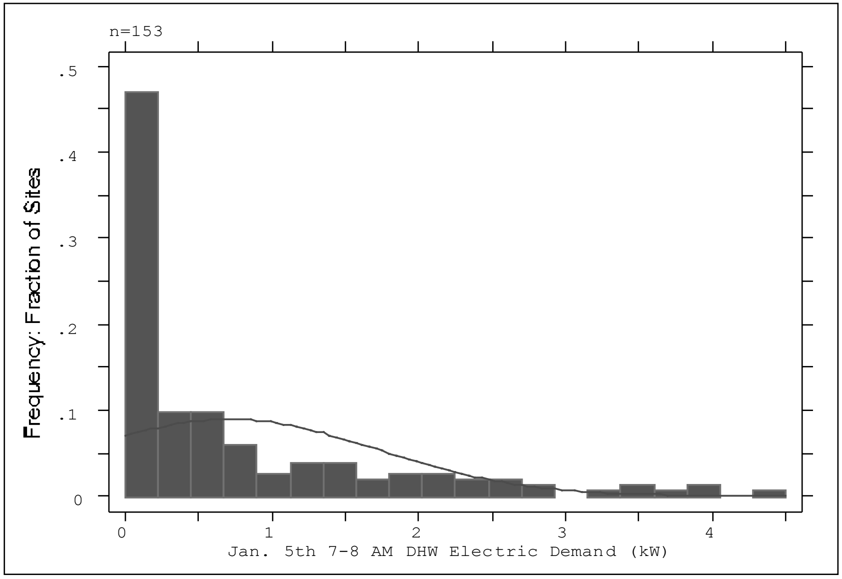
Impact of DHW Element Size on Peak Demand

At first glance, down sizing of hot water tank elements seems an idea which should reduce hot water system peak demand. Unfortunately, the project data showed the impact is very small.

We used data for January 5th of 1999 (a cold 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 and recovery takes significantly longer for each individual water heater.

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 histogram shows that over 45% of water heaters were not on during that hour in spite of no load control (Figure 12). Many of these systems were likely on the hour before or after the hour examined (related to diversity of occupant showers/schedules/absence etc.). Note that fully 45% of the tanks require no power during this time.

Figure 12. Histogram of DHW Electrical Demand at 7-8 AM on January 5th, 1999



To examine element size impact, 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 11. 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:

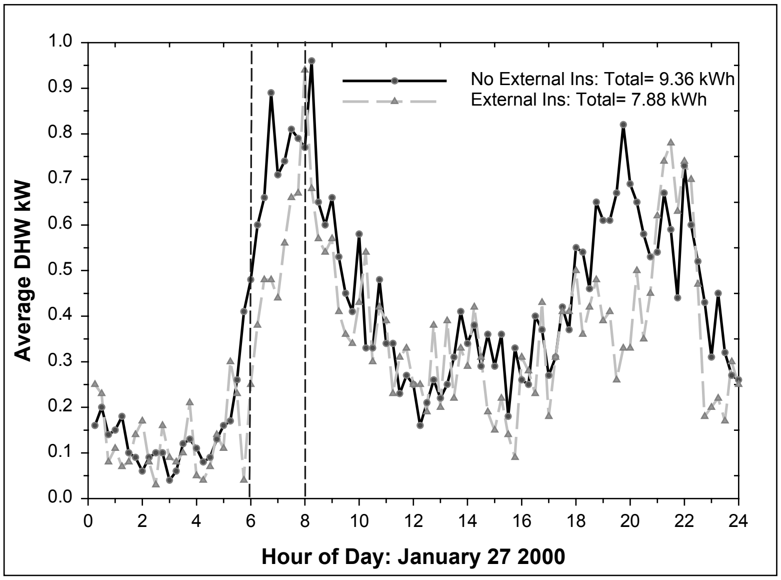
Element Size	Avg Element Size	Diversified kW	n
4-5 kW	4.596	1.248	71
3-4 kW	3.558	1.205	12

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.

Hot Water Tank Wrap

The analysis of the data on water heater electric demand showed exterior tank wraps have significant impacts on the measured hot water tank electrical demand, yet a much lower influence on energy use (Figure 13). This can be exploited to help control winter peak demand. Note the demand reduction between 6 and 7:45 AM.

Figure 13. Comparison of DHW Load Profiles for Tanks with and Without Exterior Insulation Wrap on the Winter Peak Day (Jan. 27, 2000)



Theory/Laboratory Measurements

Detailed measurements of hot water tank standby losses were performed in an environmental chamber by Ek at the Bonneville Power Administration (1984). He showed that, prior to the NAECA minimum efficiency standards of 1990, electric storage tanks 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 existing sites within the project sample which included external tank insulation wraps. The average diversified 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 0.75 kW in the sample without an external insulation wrap. The difference 0.25 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.

Pilot Tank Wrap Experiment

Based on the results, a pilot project in the fall of 1999 installed a further twenty tank wraps on electric resistance systems which had not previously had them. This produced a total of 46 hot water tanks that were insulated. The pilot project verified the earlier findings. The new tank wraps produced an average 25% reduction to peak winter morning water heating electrical demand (0.18 kW) on January 27th, 2000 when compared with unwrapped tanks which averaged 0.71 kW. Considering the overall sample of new and existing wrapped tanks, the reduction was 0.17 kW. Thus, six installed residential hot water tank wraps would save one kilowatt on the winter morning system peak. The average reduction to measured annual water heating energy was 13% or about 300 kWh per year. Tank wraps would have the simple benefit of modestly reducing monthly energy costs ($2/month) while significantly reducing winter coincident peak demand from non-load managed customers.

The largest component cost to the tank wrap pilot project was labor-- largely due to the need to custom fit many tanks.[2] Each tank wrap in the pilot project cost between $8 and $13 and it took approximately one hour to install. Valuing labor at $20 per hour, this would equate to about $30 per site. Thus, the cost per avoided winter peak kW of such a program would be $180/kW. This is likely less than half the cost of new winter peak generation. Availability of pre-cut easy to install wrap kits could potentially reduce this cost.

Conclusions

The project identified a number of influences on water heater electric demand are not commonly described. This includes the low magnitude of water heating energy in a hot climate (electric resistance systems averaged only 2,325 kWh/yr), the pronounced seasonality of water heating demand load shapes as well as the time of day influence. The project also revealed that daily outdoor air temperatures have a strong influence on water heating demand beyond the normally recognized seasonal effect. A number of additional identified impacts:

- Heat recovery units (HRUs) and solar water heaters were associated with lower demand in summer months. However, HRU systems were also found to be largely ineffective at reducing winter demand. A diagnostic evaluation showed that 30% of installed HRU systems were inoperative.
- Water heater element size was not found to statistically impact winter peak demand.
- Exterior hot water tank insulation wrap significantly reduced winter peak demand.

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[2] A large increase to the time was cutting a standard tank wrap kit to fit the tall tanks, wide ones, the short ones, the too tight to the wall ones, etc.

Acknowledgments

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