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Measured Performance and Impacts of "Drop-In" Residential Heat Pump Water Heaters

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ABSTRACT

This paper presents final results of a field evaluation of residential heat pump water heaters. This heavily instrumented field study was conducted in 17 homes across the United States over a period of 18 months. This study was unique in that the heat pump water heaters could be operated as electric resistance water heaters or as designed, heat pump water heaters with resistance backup. Field measurements of hot water usage, energy consumption, temperatures, and condensate generation provided ample data to assess the performance and efficiency of the heat pump water heater in a range of settings. The paper presents comparative results on energy efficiency, dehumidification performance, electric demand, and load factor impacts important to utilities as well as measured customer impacts in a switchover from electric resistance water heaters to heat pump water heaters.

INTRODUCTION

Water heating accounts for 12% of all of the energy used in buildings, and buildings account for one-third of all energy used in the nation (BTS 2000). Consequently, improving the efficiency of water heating can play a significant role in reducing the nation's thirst for energy. The market for residential water heaters is about evenly split between electric resistance and gas across the nation; however, there are many states where electric resistance water heater sales far outnumber gas water heaters sales. In Florida, for example, 85% of all water heaters sold are the electric resistance type.

The efficiency of electric resistance water heaters has just about topped out, and the efficiency market is tightly compressed: newly enacted efficiency standards for electric water heaters sold beginning January 2004 are only 4% higher than previous efficiency standards for electric water heaters. On that date, the least efficient 50-gallon electric resistance water heater had an energy factor of 0.90, as compared to 0.86 before then, and the most efficient are probably in the range of 0.94. There is simply not much room left for further improvement in the efficiency of electric resistance water heaters.

The heat pump water heater (HPWH), however, can provide a quantum leap in efficiency. Like an air conditioner or refrigerator, the HPWH employs a vapor compression refrigeration cycle to transfer heat from the air surrounding the water tank into the water. This can produce useful cooling and dehumidification of the air as well as providing hot water at high efficiency.

There are two basic designs of residential HPWHs. The add-on type, composed of a compressor, air-to-refrigerant evaporator, controls, and a water-cooled condenser, is installed in conjunction with an existing storage water heater. The add-on type also contains a small pump to circulate water from the existing storage water heater to the HPWH when the tank needs to be heated. In an add-on HPWH installation, piping is installed between the existing storage water heater and the HPWH, and the HPWH is wired so that the HPWH essentially replaces the function of the tank's lower element. Being retrofittable, the add-on HPWH allows the customer to retain the storage water heater. On the other hand, the integral HPWH is a single package consisting of the HPWH components as well as the storage tank. Through the combined research efforts of several organizations, a "drop-in" version of the integral HPWH has been developed, as shown in Figure 1. Termed "drop-in," the design is intended to target the large replacement market for residential electric resistance storage water heaters. The drop-in design is unique in a number of

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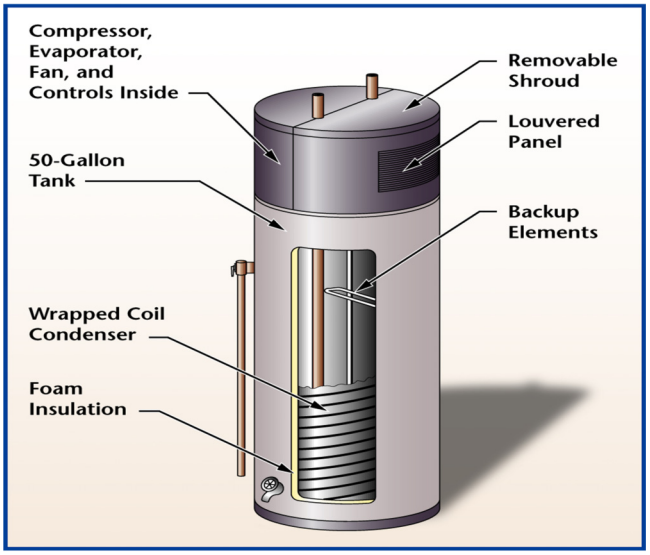

Figure 1 *Drop-in residential heat pump water heater.*

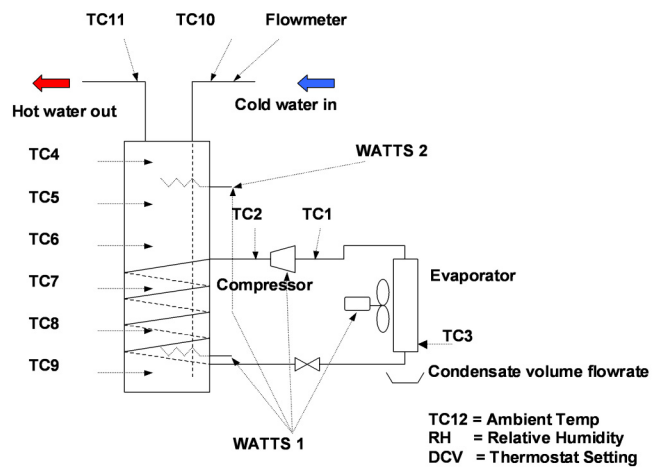

Figure 2 *Instrumentation points in HPWH field evaluation.*

ways: it uses a small (~4000 Btu/h) hermetic reciprocating compressor, a condenser consisting of tubing tightly wrapped around the lower portion of the steel tank, and upper and lower heating elements that are controlled as backup during times of heavy draws or unfavorable compressor operating conditions.

THE FIELD STUDY/EVALUATION

Following laboratory development of the drop-in HPWH design, we instrumented 17 of the drop-in HPWHs and initiated an 18-month field study in conjunction with ten utilities around the nation (Murphy and Tomlinson 2002).

Instrumentation and Data Collection

Instrumentation points and sensors were installed into each HPWH, as shown in Figure 2, prior to shipment to each test site. We used the following sensors and instrumentation locations:

- Type-T thermocouples (TC) to measure compressor suction and discharge temperatures, inlet and outlet water temperatures, evaporator and ambient temperature, as well as tank temperatures at six uniformly spaced axial locations inside the tank.
- Watt meters to measure compressor, upper and lower element, and evaporator fan power.
- Flowmeter to measure hot water flow (draws) through the tank.
- Special flow instrumentation to measure rate of condensate production at the evaporator of the HPWH.
- Moisture sensor to measure ambient relative humidity.
- Potentiometer to measure the thermostat setting of the HPWH.

We devised and used a data collection strategy that recorded data at intervals that were appropriate for the type of data to be collected:

- Ten-minute scans of ambient, compressor suction, and compressor discharge temperatures; relative humidity and thermostat setting
- Thirty-second, event-triggered scans of component electrical power, tank temperatures, and condensate production
- Two-second, event-triggered scans of inlet and outlet water temperatures and water flow rate

Data were collected and downloaded from each site on a weekly basis through a modem and phone line. In addition to data collection, we also had control over each unit so that we could operate it in two modes: as an HPWH with resistance backup (as-designed mode) or as a conventional electric resistance water heater. Our evaluation plan called for operating each unit for periods throughout the field study in each mode to determine relative performance and energy savings.

Site Selection

House designs and sites (homes) selected for the study consisted of designs typical of each region (e.g., basement, crawlspace, slab-on-grade) as well as water heater location (e.g., garage, utility room). Table 1 lists the locations and characteristics for the sites chosen.

Table 1. Characteristics of HPWH Field Test Sites

Unit	State	Residents: A = Adult C = Children	Source of Water	Unit Location	Surrounding Space: C = Conditioned S = Semi-Conditioned U = Unconditioned	Previous Electric Water Heater
1	Georgia	2 A, 2C	Well	Utility room	C	50-gal resistance
2	Georgia	2A, 2C	City	Basement	U	50-gal resistance
3	Florida	2A, 1C	City	Garage	U	None
4	S. Dakota	2A, 2C	City	Basement	C	50- gal resistance
5	Connecticut	2A	City	Basement	S	Add-on HPWH
6	Florida	2A, 3C	City	Garage	U	50-gal resistance
7	N. Carolina	2A, 1C	City	Workshop	U	50-gal resistance
8	Georgia	2A, 3C	City	Utility	U	50-gal resistance
9	Connecticut	2A, 1C	Well	Workshop	U	50-gal resistance
10	Florida	2A, 2C	City	Garage	U	50-gal resistance
11	Texas	2A	County	Laundry	C	50-gal resistance
12	Alabama	2A	County	Basement	U	Add-on HPWH
13	Alabama	2A, 5C	County	Laundry	C	80-gal resistance
14	Tennessee	2A, 2C	City	Garage	U	80-gal resistance
15	Tennessee	None	City	Closet	S	None
16	Washington	2A, 2C	City	Basement	U	52-gal resistance
17	Oregon	2A, 2C	City	Basement	U	50-gal resistance

Note: Unit 15 was in an unoccupied house; 64.3 gal/day draws done with a timer-operated valve

HPWH Performance

The field study began at each site as the existing water heaters were replaced by drop-in HPWHs. Because of this staggered installation of the HPWHs, initiation of data collection took place over a six-month period. Data from each site were collected using on-site dataloggers, downloaded on a weekly basis, and data summaries for the week were prepared and analyzed. For most of the 18-month period of the experiment, the units were operated in the "as-designed" mode (the HPWH mode). This mode places priority on compressor use, unless compressor conditions fall outside of an acceptable operating envelope of discharge and suction temperatures, or in the event of unusually heavy draw(s). As expected from the small capacity of the compressor, compressor runtimes were long, typical of what would be found with a refrigerator compressor. Figure 3 provides a summary of weekly runtimes (left axis) for the upper element, the lower element, and the compressor and weekly hot water (HW) consumption (right axis) for each of the units. In this figure, the stacked bars show that the total time of operation of units varied from 32 to 85 hours per week, depending on the field test site and location. With the exception of unit 16, practically all hours of operation were attributed to compressor operation. Unit 16, located in Seattle, used more resistance heating than the other units for several reasons: (1) large hot water consumption, (2) significant hot water consumption concentrated in a short time (mornings), (3) cold water supply temperatures (~45°F), and (4) cool ambient temperatures (avg. 58°F). These factors reduced the ability of the compressor alone to meet the hot water demand. For all units, weekly hot water use varied from 805 gallons per week to as little as 164 gallons per week—a strong function of the number of household residents.

Our ability to operate each unit as a conventional electric resistance water heater as well as an HPWH was essential in determining the delivered efficiency of the HPWH. Figure 4 shows a scatter plot of the weekly electrical energy consumption for units operating in the HPWH mode and for operating at other times in the conventional (resistance WH) mode as a function of the heat delivered to the customer in the form of hot water. In either mode, it is clear that electrical consumption (kWh) grows with the amount of heat delivered in the hot water to the customer. Moreover, Figure 4 suggests that the electrical energy consumption drops by about half in moving from the resistance mode to the HPWH mode.

In a further look at the data from the standpoint of efficiency, we used the concept of "delivered efficiency (COP)" to be the quotient of the electrical energy provided to a unit and the total heat provided to the customer in the form of hot water. Since units could be operated as conventional resistance water heaters as well as HPWHs, we were able to determine the

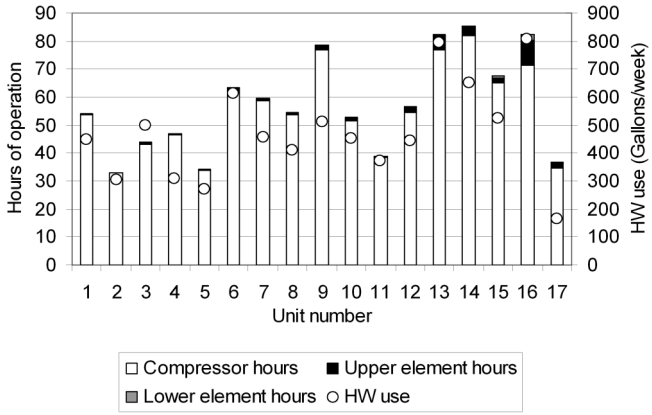

Figure 3 *Average weekly hours of compressor and upper and lower element operation; average weekly HW consumption.*

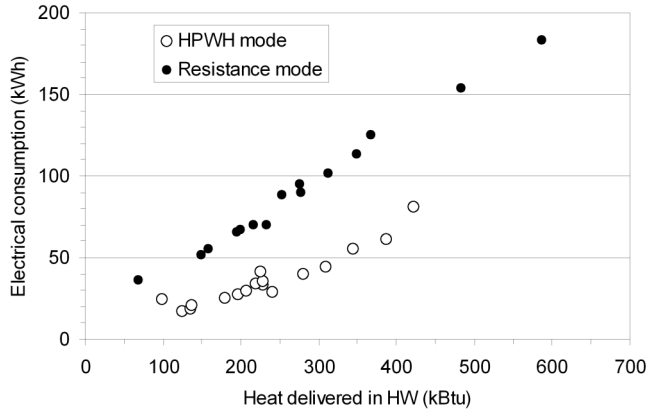

Figure 4 *Average weekly performance comparison with units operated in HPWH mode and resistance mode.*

delivered efficiency of each unit operated in either mode. With units operating in the resistance mode, we measured units' average efficiency to be 0.86, and in the HPWH mode (as designed), we measured average efficiency to be 2.00. With the HPWH operating as designed, we determined energy savings by comparing actual electrical energy consumption with the electrical energy that the unit would have used at the measured efficiency while in resistance mode operation. The results of this analysis for each of the 17 units are shown in Figure 5. These results show that for all units, the energy savings range from 41% for unit 16 located in a Washington basement to 62% for Georgia unit 1 located in the conditioned space. The weighted average energy savings was 55% from this field evaluation.

As shown in Figure 5, unit 17 (Oregon basement location) showed a 54% energy savings despite its low COP (COP = 1.18). The reasons for the low COP with unit 17: cool year-round ambient temperatures (48°F), high WH thermostat setpoint (145°F), and very low water use (164 gal/week), each of which contributes to high relative standby losses from the tank. Even when operated in the resistance mode, the COP of unit 17 was 0.54. Therefore, rather than an outlier, the data shown on unit 17 is real and accurately represents the performance of the HPWH under these conditions.

Customer Impacts

In any changeover to a new technology for heating, cooling, or water heating, there is the potential for customers to be impacted by the way that the new product performs. Customers are impacted by the delivery of hot water; therefore, it was important to evaluate this issue. The two-second, event-initiated data on hot water flow and temperature allowed us to define draws and to calculate information contained in them. We defined the initiation of a draw event as a data record

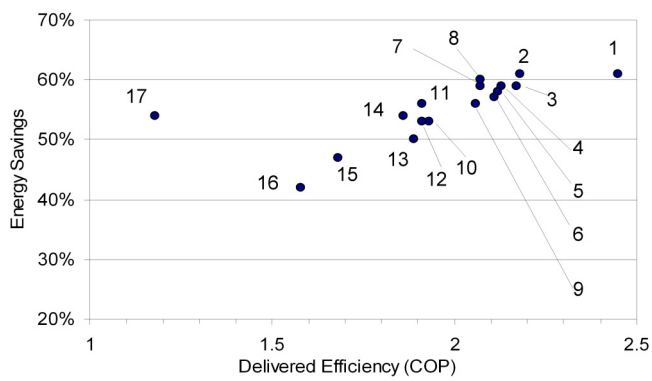

Figure 5 *Efficiency and energy savings for each field unit. Unit number designation attached to data points.*

occurring more than two seconds after a previous record in the data file. We defined the conclusion of a draw by looking to the subsequent record to determine if it occurred more than two seconds ahead in time. This process allowed us to identify all draws, including those as brief as two seconds in duration. Interestingly, Figure 6 shows that there is wide variability in draw frequency (80-140 draws/day), and there is also wide variability in hot water (HW) usage (40-80 gal/day) for Unit 8 located in a Georgia utility room off of the garage. Similar variabilities exist for other sites, as shown in Figures 7 and 8. Beginning and ending temperatures recorded associated with each draw enabled us to pin down the delivery temperature at the end of the draw.

Hot Water Deficits. We used draw data to address the potential issue of hot water runouts (deficits) between HPWH and resistance mode operation. We used the arbitrary defini-

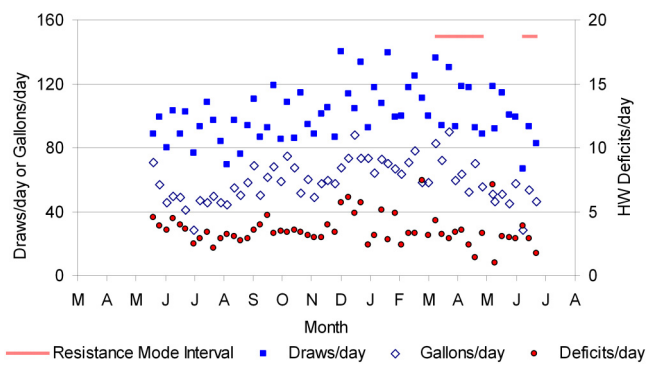

Figure 6 *Draw and hot water (HW) deficits—unit 8.*

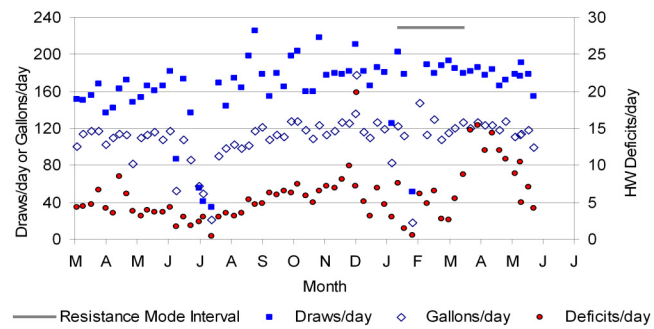

Figure 7 *Draw and hot water (HW) deficits—unit 16.*

tion of a deficit as a draw that had an ending temperature of 105°F or lower. To be sure, there are many draws, particularly short ones, in which the ending temperature does not reach 105°F, yet a customer would not term them a runout. However, since we conducted the field study with the HPWHs in the resistance mode for part of the time, changes in runouts according to our definition of "HW deficit" could be identified. Figure 6 shows information developed for unit 8—an HPWH located in an unconditioned utility room in Atlanta. The interval over which unit 8 operated as a resistance water heater is also shown in Figure 6. The data points show that over the test period, the number of daily draws typically ranged from 80 to 120, and the total amount of water in these draws ranged from 40 to 80 gallons. There seemed to be little change in draw consumption with month (slight increase in wintertime due to colder incoming water), and no change in draw pattern when the unit was operated as a resistance water heater. Figure 6 also shows the average number of hot water deficits per day. Deficits were typically in the range of <5 deficits/day, and the deficit rate did not seem to depend on the mode of operation of the HPWH. This indicates that switching from a conventional electric resistance water heater to the HPWH would have little, if any, effect on hot water draw patterns or hot water deficits.

We performed the same analysis on other units. Figure 7 shows the results for unit 16, located in a basement in Seattle. Unit 16 experienced more draws and used more water than unit 8; however, the average draw appeared to be smaller. Deficits appeared to grow marginally during the wintertime due to cold ambients and cooler initial pipe temperatures. However, as with unit 8, there did not appear to be any relation between operating mode (HPWH or resistance) and hot water deficits. Unit 1 was located fully in the conditioned space in an Atlanta house. The draw performance for this unit is shown in Figure 8. It can be seen that the average hot water draw was about one gallon and that the deficits were small. The fact that unit 1 is located inside the house, the house is in a warm climate, the HPWH is relatively close to all of the hot water fixtures in the

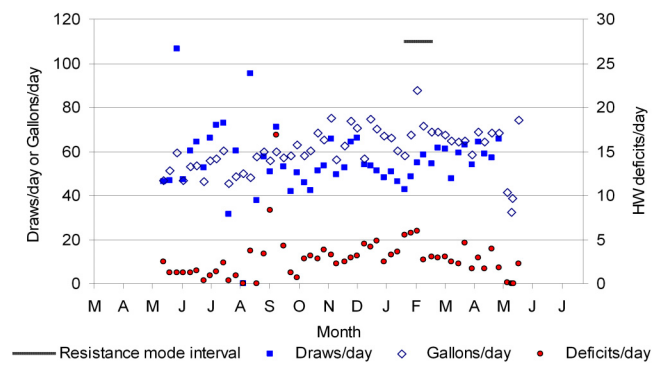

Figure 8 *Draw and hot water (HW) deficits—unit 1.*

house, and the typical draws are small, suggests that deficits would be small, as they appeared to be from Figure 8. As before, there was no evidence that the HPWH retrofit has any effect on hot water deficits.

Cooling and Dehumidification. Cooling and dehumidification provided by the HPWHs were also determined. We calculated the net cooling from the HPWH from first principles,

$$Qc = \Delta U + \Sigma Qd + Qloss - Ein \,, \qquad (1)$$

where

Qc = net cooling (cooling at the evaporator – compressor shell heat loss),

ΣQd = total thermal energy in all draws from the tank,

$Qloss$ = heat loss from the tank to ambient,

Ein = electrical energy to the tank, and

ΔU = internal energy change of the tank.

With the exception of $Qloss$, all four terms on the right side of Equation 1 could be determined from field data. The change in tank internal energy (ΔU) was determined using the six tank temperature sensors, and the total energy in the hot

water removed from the tank (ΣQd) was determined from the draw analyses. Tank heat loss ($Qloss$) was determined using the tank heat loss coefficient measured in the laboratory prior to the field test and field-measured data on average tank temperature and ambient temperature. From these data, the net total cooling, Qc, was determined. We measured dehumidification in the field using a custom device that determined the volume of condensate generated before it was sent down the drain.

The results of these measurements and calculations for unit 8 in an unconditioned space in an Atlanta house are shown in Figure 9. The total cooling rises as summer turns into winter, principally due to cooler incoming water temperatures and cooler ambient temperatures. During the resistance mode intervals, there was no compressor operation and, consequently, no cooling produced. Condensate was produced at the rate shown for the summer, but little condensate was produced during the winter. Consequently, it appears that the HPWH in an unconditioned space helps to dehumidify the space during the summer. The differences in dehumidification produced in the same month for two successive years could be weather-related or caused by other unmeasured factors.

The results of cooling and dehumidification measurements for unit 1 in a conditioned space in an Atlanta house are shown in Figure 10. Total cooling produced by the HPWH increases from summer to winter, as in the case for unit 8. Interestingly, for most of the test period, HPWH evaporator temperatures were not low enough to do much dehumidification, i.e., the house air-conditioning system accomplished the dehumidification. However, during the March-May period when the house's air conditioner was not being used, the HPWH did perform dehumidification as shown. It should be pointed out, however, that although the HPWH accomplished essentially no dehumidification during the summer, it still provided cooling and reduced the total cooling load of the home's air-conditioning system by approximately 0.2 tons. We conclude from this that the HPWH in a conditioned space may not accomplish dehumidification effectively; however, an HPWH located in an unconditioned or semi-conditioned space (e.g., a basement) would accomplish dehumidification.

UTILITY IMPACTS

Electricity producers provide generation capacity sufficient to meet the aggregate electric demand from residential, commercial, and industrial customers. A key measure of the benefit of a technology, such as the HPWH, to utilities is the diversified demand—a measure of the average demand (kW) that the technology distributed to a large number of customers would impose on the utility. In the HPWH field study, the average diversified electric demand for a subset of units operated in the HPWH mode for a period and in the resistance mode for another period was determined. This analysis was done to evaluate the impact of a changeover from resistance storage water heaters to the HPWH. For this analysis, six of the units were operated in the resistance mode for six weeks during the winter and again during the summer of the study. We chose a 15-minute demand interval as representative of the interests of most utilities. Data from each of these four periods for the six units were aggregated and used to determine the diversified demand plots shown in Figures 11 and 12. As expected, the HPWH mode as well as the resistance mode produced the "double hump" that is characteristic of residential electric water heaters due to heavy hot water consumption in the morning and in the evening. Figures 11 and 12 show that the HPWH provides a reduction in diversified demand during both seasons. Interestingly, Figure 11 shows that the demand of the HPWH is higher than the demand of a resistance water heater from midnight until about 4 a.m.; during this time interval, electric generation costs are low. Summertime diversified demand for the HPWH is lower than for the resistance counterpart in the late morning and afternoon—times when utilities are experiencing peak demand. Moreover, the HPWH is also providing some cooling during this peak period and, to a small degree, is offsetting some of the air-conditioning demand. Overall, the field study suggests that the HPWH exhibits an electric load profile that is attractive to utilities.

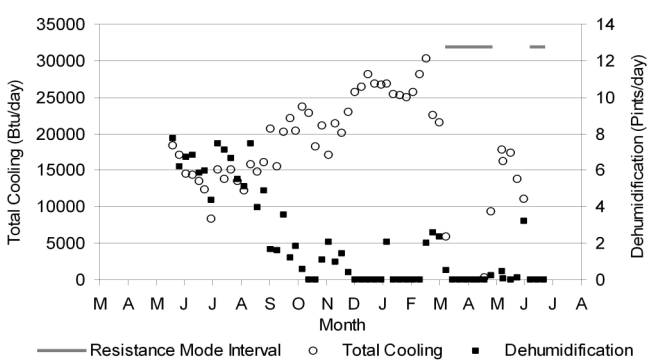

Figure 9 *Cooling and dehumidification performance—unit 8.*

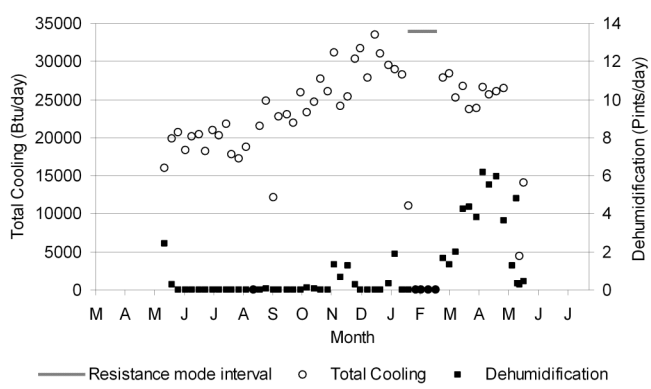

Figure 10 *Cooling and dehumidification performance—unit 1.*

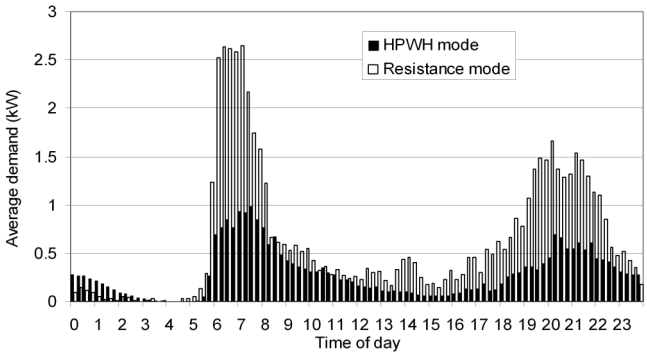

Figure 11 *HPWH/Resistance WH wintertime diversified electric demand comparison—15-min basis.*

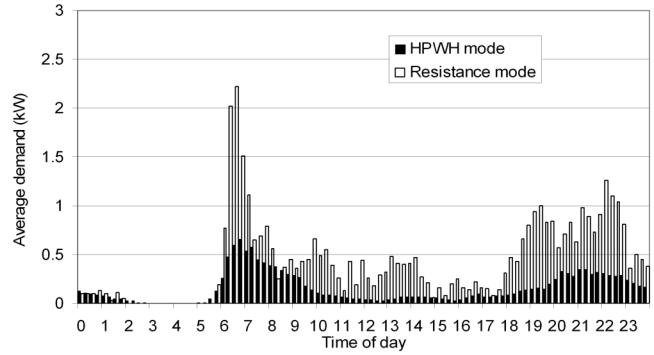

Figure 12 *HPWH/Resistance WH summertime diversified electric demand comparison—15-min basis.*

SUMMARY AND CONCLUSIONS

The national field study determined that, on average, the drop-in residential HPWH would produce an energy savings of 55% in typical homes in the locations tested. Savings as high as 62% were found where the HPWH is located in the conditioned space or in a warm Florida garage, and savings as low as 41% were found for a unit located in a cool basement in Washington State. Hot water consumption patterns in the study varied from 23 gallons per day to more than 110 gallons per day, with an average of 67.3 gallons per day. Individual hot water consumption (gallons per day per capita) varied from 9.9 to 31.7 and averaged 19.3 for the study. The study determined that the HPWH would not aggravate hot water runouts (deficits) as might have been expected due to the fact that the low heating capacity of the compressor (~4,000 Btu/h) is small compared to the heating capacity of the elements in a conventional resistance water heater. We found that the dehumidification benefit of the HPWH depends greatly on its location. In a conditioned space installation, the HPWH may not offset the dehumidification produced by the space-conditioning system (air conditioner). However, in an unconditioned or semi-conditioned installation, the HPWH provides dehumidification up to about 6 pints per day. Evaporator cooling was found to increase with ambient temperature, with hot water production and with lower overall condensing temperatures. On average, evaporator cooling amounted to about 30,000 Btu/day.

The drop-in HPWH appears to have a beneficial impact on electric utilities for both summer and winter. In particular, morning reductions in electric demand were found to be about 1.4 kW and evening reductions were about 0.5 kW. Moreover, HPWH operation in the afternoon reduces that portion of a utility's electric demand associated with water heating and at least minimally offsets some electric demand due to air conditioning.

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