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Multifamily Heat Pump Water Heater Evaluation

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Alliance for Residential Building Innovation (ARBI)

November 2013

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Unless otherwise noted, all tables were created by the ARBI team.

Definitions

ARBI	Alliance for Residential Building Innovation
COP	Coefficient of performance
DHW	Domestic hot water
DOE	U.S. Department of Energy
HPWH	Heat pump water heater
HVAC	Heating, ventilation, and air conditioning
kBtu	Thousand British thermal units
kW	Kilowatt, electrical demand
kWh	Kilowatt-hour
RH	Relative humidity
TRNSYS	TRaNsient System Simulation program
WVCP	West Village Community Partnership
ZNE	Zero net energy

Executive Summary

More than 40% of U.S. households (DOE 2010) provide domestic hot water using electric resistance storage water heaters. There is a significant opportunity to improve water heating energy efficiency in these households through the use of heat pump water heaters (HPWHs), which offer potential energy savings of 50% or more. Sales of HPWHs serving individual homes or apartments have increased in recent years through a combination of aggressive manufacturer marketing and utility incentives. Evaluations of HPWHs serving a central water heating system have not been widely completed, making this effort valuable in documenting the performance and identifying issues. In this project the Alliance for Residential Building Innovation team monitored the performance of a central HPWH installed on student apartments at the University of California at Davis' West Village Zero Net Energy community. The HPWH system, one of 32 currently installed at West Village, was monitored in detail over a 16-month period. Monitoring results were used to validate a TRNSYS simulation model. The validated model was then applied to six U.S. climates to evaluate performance using local weather and utility rates.

The nominal 127,000 Btu/h E-Tech air source HPWH was installed with two 120-gal storage tanks in series (with 54-kW electric elements for supplemental heating) to provide hot water to a 12-unit apartment building serving 32 occupants. The system was monitored from October 2011 through February 2013. As the monitoring was initiated in 2011, it was immediately determined the HPWH was not operating properly, due primarily to a lack of contractor familiarity with the technology. The initial problems were corrected and the unit operated well until July 2012 when the evaporator fan motor failed and required replacement. Steady-state operating coefficients of performance (COPs) matched well with the manufacturer's ratings, although both heating capacities and power demand were 10%–20% lower than nominal ratings, primarily due to higher HPWH inlet water temperatures and lower system flow rates through the HPWH heat exchanger. Although steady-state operating data demonstrated COPs of 3.0–4.0, monitoring over the 16 months indicated that operating cycles were frequently short, resulting in lower average efficiencies due to performance degradation during system startup. Cycling degradation and fairly high standby parasitic energy consumption degraded the 3.0–4.0 COP steady state readings to an annual average COP of 2.12. The performance degradation impact was most pronounced in the summer months when lower hot water loads, increased effect of standby parasitic, and shorter compressor run cycles resulted in monthly average COPs of 1.7–1.9.

Two weeks of 15-min interval field monitoring data were used as inputs to validate a TRNSYS model of the "as-built" HPWH installation. The model was then extended to six U.S. climates (Phoenix, Houston, Sacramento, Seattle, Denver, and Chicago) to project performance and estimate operating costs relative to conventional gas and electric storage base-case scenarios. Annual energy savings relative to an electric base case scenario ranged from 49%–59%, with annual savings of $1,920–$3,475/year using local utility rates (~ 6- to 10-year simple paybacks). Savings relative to a gas water heating base case were found to be more challenging, with none of the six locations projected to achieve a 10-year simple payback given the current low cost of natural gas in most of the United States.

High level project conclusions suggest that although 50% or more savings are easily achievable relative to electric resistance water heating systems, greater savings could well be realized by optimizing system performance. Increasing the average compressor duty cycle through modified

controls, use of variable speed or two-stage compressors, and/or increased storage volumes would likely benefit the heat pump performance by increasing steady-state operation. Greater attention to reducing standby parasitic energy would also contribute to improve seasonal performance, especially in milder climates where HPWHs should demonstrate the maximum savings potential relative to conventional electric resistance water heating. Finally, the technology is still not mature and is therefore constrained by a small market share, which translates to high equipment costs, limited contractor familiarity, and difficulties in providing a robust service infrastructure.

The primary intended audience for this study is water heating researchers, utilities, and manufacturers of the larger central HPWHs. Early efforts to document the performance of these systems and identify improvement options can lead to better product offerings, improved design methods, and more thorough operation and maintenance procedures.

1 Introduction

1.1 Background and Motivation

More than 40% of U.S. households (DOE 2010) heat domestic hot water (DHW) using electric resistance storage water heaters. There is a significant opportunity to improve water heating energy efficiency in these households through the use of heat pump water heaters (HPWHs), which offer expected energy savings of 50% or more. Sales of HPWHs serving individual homes or apartments have increased in recent years through a combination of aggressive manufacturer marketing and increasing utility incentives. While there has been significant attention focused on the monitoring and evaluation of single family HPWHs (Amaranth and Bush 2012; PG&E 2010), there are very few available data on the performance of larger central HPWH systems (Gray 2010). Part of this can be attributed to the fact that there have not been many central HPWH installations monitored to date and the product options are much more limited than the single family scale HPWHs.

In this project the Alliance for Residential Building Innovation (ARBI) team monitored the performance of a central HPWH installed on a 14,200-ft^2 student apartment building (12 apartments) at the University of California-Davis' Zero Net Energy West Village community. The nominal 10.5-ton HPWH serving the building was coupled to two 120-gal electric hot water tanks (in series), which provided both storage capacity and 54 kW of supplemental resistance heat. With increasing interest in community-scale zero net energy (ZNE) projects, it is important to develop case studies that document cost-effective solutions and lessons learned in a range of climates and applications. This will help identify strategies that work reliably and those that may need more development and support through the implementation process.

Since previous field testing of single-family HPWHs showed lower than rated field performance due to a variety of factors including hot water load intensity, unit location, and other issues, monitoring of the central HPWH installation will be beneficial in documenting field performance of a commercial-scale system under varying climate and use conditions. The student-occupied apartments also represent a hot water usage pattern that is likely more diversified than those for typical single -family applications.

This project addresses a key Building America Hot Water Standing Technical Committee gap and barrier:

> Evaluating HPWH field performance to characterize how climate, behavior, hot water loads, and system configuration affect performance and customer satisfaction.

1.2 Project Description

The University of California-Davis West Village project, located approximately 15 miles west of Sacramento in California's hot-dry Central Valley climate, was the largest ZNE mixed-use community under construction in the United States[1] as of 2010. The 130-acre project will ultimately provide housing for almost 2,000 students, 343 single family homes for faculty and staff, and also include a town center with both office space and retail. To date, a mixed-use town center and much of the student housing have been completed, while single family home

[1] http://www.news.ucdavis.edu/search/news_detail.lasso?id=10464

construction is slated to begin in late 2013. The project's ZNE design approach focused on integrating cost-effective energy efficiency measures with renewable generation in the form of photovoltaics and a biogas system utilizing campus agricultural waste. In addition to the HPWHs, installed energy efficiency measures include:

- High efficiency air source heat pumps for space heating and cooling
- Increased wall and attic insulation and attic radiant barriers
- Home Energy Rating System inspections on insulation quality, duct leakage, and envelope leakage
- High performance windows
- 100% high efficacy lighting
- ENERGY STAR® appliances.

Although space conditioning heat pumps and central HPWHs are generally not common in the Davis area due to the widespread availability of comparatively inexpensive natural gas, they were implemented in the student apartment design as a key component of an all-electric energy efficiency strategy.

For the student apartments, 37% source energy savings were projected over the B10 Benchmark in hot-dry climates (Dakin et al. 2012). These measures, and specifically the package of measures, have the potential to lead to market-ready solutions that cost-effectively provide comfort in multifamily buildings with efficient, safe, and durable operation.

Figure 1 shows the town center square with retail/office space on the ground level and apartments above, and Figure 2 provides a broader view of the project with student apartment buildings and the leasing/student recreation center to the left. Most of the apartment buildings contain 12 apartments with a mix of two-, three-, and four-bedroom units.

Figure 1. View of town center square

Figure 2. View of student apartments and leasing/recreation center

1.3 Research Questions

The primary objective of this project was to evaluate the performance and efficiency of the central HPWHs as a strategy to provide efficient electric water heating for multifamily applications where natural gas is unavailable, or where favorable electricity rates provide a competitive environment relative to gas water heating.

Research questions include the following:

1. What are the measured performance and reliability of the central HPWH and how do these compare to expectations from modeling and manufacturer claims?
2. How viable is the central HPWH system compared to other conventional options under varying retail rate scenarios?
3. Under what load and ambient conditions does the HPWH fail to meet the load and how frequently does this occur?
4. How does the HPWH sizing to peak load ratio compare to typical single family applications and what are the performance implications?

Proposed monitoring and modeling efforts will be used to provide answers to these questions and determine how effective the approach is in contributing to meeting Building America performance goals. Overall incremental costs and energy use of the HPWH will be used to evaluate the costs and benefits of a centralized HPWH system for multifamily residences for various conventional system types in different climates.

2 Methodology

2.1 West Village Heat Pump Water Heater Specification and System Design

A 2012 ARBI study (Dakin et al. 2012) documented West Village design processes surrounding the development of the package of energy efficiency measures. The 2012 report presents the 2009 evaluation of heating, ventilation, and air conditioning (HVAC) and water heating options completed in conjunction with the West Village Community Partnership (WVCP, the West Village project developers). The developers selected individual apartment gas storage water heaters as the reference base-case system type for comparison to higher efficiency alternatives. Incremental costs for the central HPWH design were initially estimated at $12,800 per building (or slightly below $1,100 per apartment). Once bids were received, the incremental cost was found to be only $500 per apartment. Further cost savings were realized by eliminating gas lines and venting, and freeing up some additional interior floor space required for the individual water heaters. Factoring this in, the developer determined that the central HPWH was a zero incremental cost item. With that information and a desire to pursue an all-electric solution for the student apartments, WVCP chose to install central HPWHs.

The mechanical engineer of record for the project worked with A.O. Smith to select an appropriate piece of equipment. The engineer selected an A.O. Smith (E-Tech[2]) WH115-HTC HPWH to satisfy each building's DHW loads. Specifications of the unit and the HPWH installation can be found in Table 1 with a system schematic shown in Figure 3. The manufacturer suggested that the system be configured with the HPWH maintaining 140°F water temperatures in the primary storage tank. Resistance elements in the two electric storage tanks were scheduled to maintain minimum tank temperatures of 120°F, allowing the HPWH to meet the bulk of the water heating load. A tempering valve downstream of the second storage tank was set to limit the supply water temperature to the recirculation loop at 120°F. A hot water recirculation loop pump serving the building is controlled by both a return water temperature sensor and a timer that shuts it off during part of the night.

Table 1. HPWH Installation Characterization

Parameter	Description
Building Size (ft^2)	14,200
Number of Apartments	Six @ 4 bedroom, six @ 2 bedroom
Number of Stories	Three
HPWH Make and Model	AO Smith (E-Tech) WH115-HTC
Nominal Capacity (Btu/h)	127,000 (at 85°F dry bulb, 50% RH, 100°F inlet water temperature, 25 gpm)
Storage Configuration	Two 120-gal electric tanks in series (54 kW in each tank)
Distribution System	Time/temperature recirculation control; 1¼-in. insulated hot water supply and return lines

[2] A.O. Smith purchased ETECH in 2009.

2.2 Heat Pump Water Heater Monitoring Approach

The monitoring strategy focused on characterizing HPWH performance (capacity, power, and efficiency) as a function of hot water load, varying return water temperatures, and outdoor temperature effects. A minimum 12-month monitoring period was planned to adequately capture seasonal performance effects associated with climate, cold water inlet temperature variations, and hot water load variations during the course of the academic year. Water heating energy flows were calculated on a 15-s interval basis using water side measurements (flow times temperature difference) as shown in Equation 1. Energy flows were totalized and reported on a 15-min interval. HPWH efficiency (Equation 2) was calculated on a 15-min basis by dividing the HPWH energy delivered by the energy consumed. The HPWH schematic shown in Figure 3 depicts the location of the installed monitoring equipment, while Figure 4 and Figure 5 show the outdoor HPWH unit and the configuration of the indoor mechanical room with flow meters and temperature sensors installed.

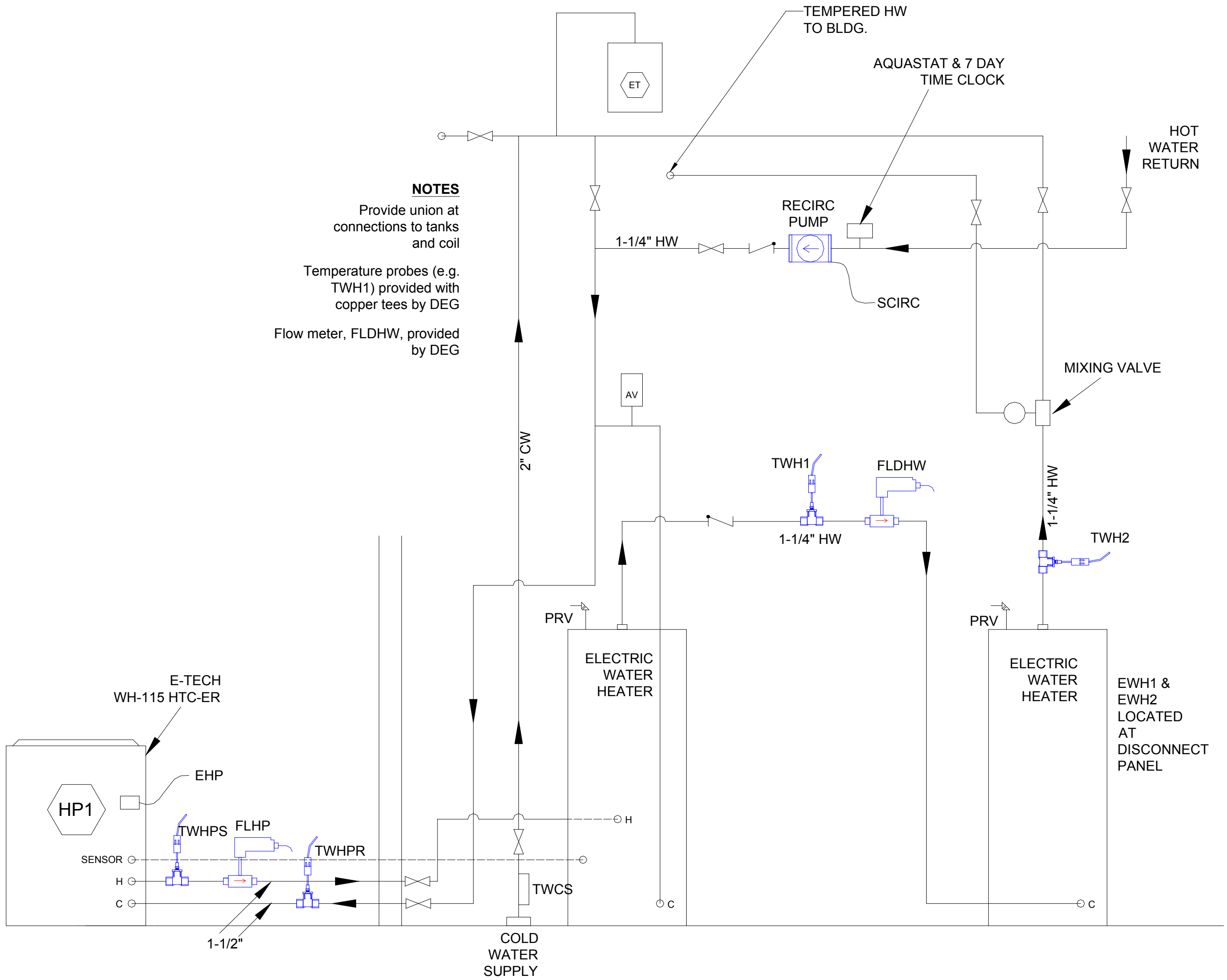

Figure 3. Water heating system configuration and monitoring sensor location

Figure 4. Monitored HPWH outdoor unit

Figure 5. 120-gal electric resistance storage tanks with piping and monitoring sensors

$$Q\ (kBtu) = 8.33 * FLOW * (THOT - TCOLD) * 0.001 \quad (1)$$

where,

FLOW = 15-s flow to the HPWH (gal/15 s)

THOT = temperature leaving the HPWH condenser (ºF)

TCOLD = temperature entering the HPWH condenser (ºF)

$$\text{Efficiency (coefficient of performance [COP])} = (0.001 * Q\ (kBtu)) / (HPWH\ kWh * 3.413) \quad (2)$$

where,

Q (kBtu) = summed 15-min HPWH heat delivery (Btu/15 min)

HPWH kWh = HPWH energy consumed over 15 min

Table 2 lists all the measurement points monitored on a continuous basis and Table 3 lists the sensors and their performance specifications. A programmable Thermo Fisher Scientific Datataker data logger and cellular modem were used for continuously collecting, storing, and transferring data to the ARBI host computer.

Table 2. Measurement Points

Abbreviation	Description	Location	Sensor Type
TAO	Outdoor air temperature	Shield location near HPWH	RTD, 4–20 milliAmp
RHO	Outdoor relative humidity (RH)	Shield location near HPWH	RTD, 4–20 milliAmp
TWRECIRC	Water temperature, recirculation	Mechanical room—DHW	Immersion thermocouple
TWHPS	Water temperature heat pump supply	Mechanical room—DHW	Immersion thermocouple
TWHPR	Water temperature heat pump return	Mechanical room—DHW	Immersion thermocouple
TWH1	Outlet water temperature, electric water heater #1	Mechanical room—DHW	Immersion thermocouple
TWH2	Supply water temperature, electric water heater #2	Mechanical room—DHW	Immersion thermocouple
TWCS	Cold water inlet temperature	Mechanical room—DHW	Pipe surface thermocouple
FLHP	Flow to HPWH	Outdoors, near heat pump	Flow meter
FLDHW	Flow, DHW	Mechanical room—DHW	Flow meter
EHP	Heat pump energy	Mechanical room—panel	Power meter
EWH1	Electric heater #1 energy	Mechanical room—panel	Power meter
EWH2	Electric heater #2 energy	Mechanical room—panel	Power meter
SCIRC	Recirculation pump status	Mechanical Room—DHW	Status
FLRecirc	Recirculation return flow	Mechanical Room—DHW	Flow meter

Table 3. Sensor Specifications

Type	Application	Manufacture/ Model	Signal	Span	Accuracy
RTD	Outdoor temperature and RH	Vaisala HMY60	4-20 mA	14°–140°F 0%–100%	± 0.5% °F ± 2% RH
Type T Thermocouple	Immersion water temperatures	Omega Type T	~11mV@ 500°F		± 0.4%
Flow Meter	Water flow	Onicon F-1100	Pulse	1–130 gpm	± 0.5%*
Power Monitor	HPWH power and electricity storage	Wattnode/ WNB-3D-240-P	Pulse	CTA/60	± 0.5%
24VAC Relay	Status	Hawkeye	Dry contact	N/A	N/A

* 0.5% at the calibration flow rate (± 1%–2% of reading over a 50:1 flow range)

2.3 Evaluation Approach

The planned approach for evaluating HPWH performance involved utilizing full-load data to develop a performance map describing system performance as a function of inlet water temperatures and outdoor air temperature. The as-built HPWH configuration at West Village could then be modeled using TRNSYS v17 Type 941 heat pump model (TESS 2011) and the capacity and power performance maps. The Type 941 model is a single-stage air-to-water heat pump model that takes the user-supplied performance map (with fractional capacity and power multipliers based on entering water and air temperature) and applies the factors to user-input nominal performance ratings. The model interpolates on these steady-state performance maps to determine the output capacity and power during each time step when the HPWH operates. A Type 534 storage water heater model was used for each of the 120-gal electric storage water heaters. The storage model utilized 10 vertically stratified nodes in the first tank and eight nodes in the second tank, with greater resolution in the first tank needed to capture the connections to and from the HPWH.

Two weeks of field data, typical of fall and winter full occupied schedules, were selected to be used in the model validation process. Monitored outdoor temperatures, inlet cold water temperatures, and hot water flows were used to drive the model. The goal of the validation effort was to match the weekly energy generated by the HPWH and weekly energy consumed by the system. It was difficult to match the model with the monitoring data on a short time scale, since the TRNSYS simulation needed to be run on a 15-s time scale to adequately represent system control characteristics. Since collected hot water usage data were logged on 15-min intervals, one could only distribute the flow uniformly over the 60 15-s TRNSYS time steps, introducing some level of inaccuracy. Validation efforts included adjusting the number of tank stratification nodes, the mixing rates between nodes, tank port locations, pipe insulation characteristics, and aquastat and temperature sensor locations. All efforts were made to model the “as-built” system with minimal adjustments of known physical parameters.

The final step in the evaluation process was to exercise the validated model through various climates using a typical standard draw profile based on ASHRAE Service Water Heating profiles (ASHRAE 2011) for apartments. Figure 6 plots the assumed fraction of the hourly hot water load assumed in this study based on the ASHRAE profiles. A daily nominal hot water load of 11 gal/person-day was assumed with a total building occupancy of 42 people. Typical Meteorological Year data (TMY3) for each climate were used to drive the model with outdoor ambient air temperature, humidity, pressure, and inlet water mains temperature. Hot water usage was adjusted for each climate (ranging from –4% in Phoenix to +7% in Chicago) to adjust for variable distribution loss impacts due to climate (Backman and Hoeschele 2013). During model validation, the monitored recirculation flow rate and temperatures were fed into the system as an input. For the climate performance evaluation, the hot water end use loads (i.e., delivered hot water at the fixtures) were increased by 30% to approximate the "typical" magnitude of recirculation loop thermal energy impacts derived from a recent monitoring study (Zhang et al. 2012).

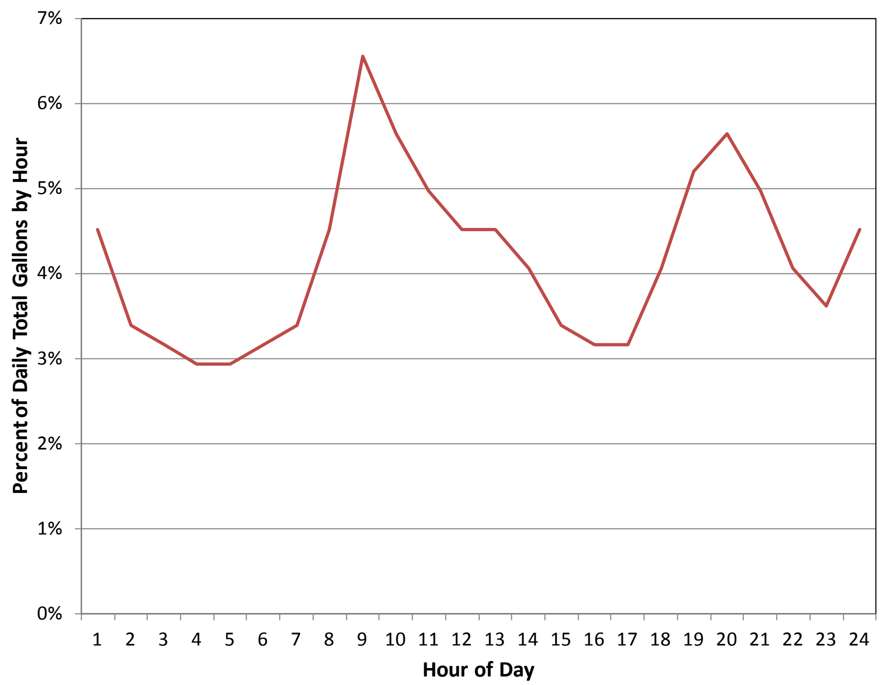

Figure 6. Assumed multifamily hot water use profile

Assumed utility rates for each location (shown in Table 4) were calculated based on statewide information provided by the Energy Information Administration.[3]

[3] http://www.eia.gov/electricity/sales_revenue_price/pdf/table5_a.pdf

Table 4. Assumed Utility Rates

Location	Gas Rate ($/therm)	Electricity Rate ($/kWh)
Phoenix	1.485	0.1108
Houston	0.993	0.1108
Seattle	1.195	0.0828
Sacramento	0.974	0.1478
Denver	0.800	0.1127
Chicago	0.869	0.1178

3 Results

3.1 System Commissioning and Heat Pump Water Heater Operational Issues

The value of proper commissioning was made evident as part of the ARBI team's experience with the West Village HPWH. After the monitoring system was installed and commissioned in mid-September 2011 (shortly after the first apartments were occupied by the students), the ARBI team immediately observed that the HPWH was not operating properly. The evaporator fan and HPWH circulating pump were running continuously, giving the impression that the HPWH was operating, although in reality the entire water heating load was being met by the backup electric storage water heaters. This was not intuitively obvious to the installing plumbers and the site maintenance team given their lack of familiarity with the technology and the shortcomings of the HPWH control interface.[4] The fact that the compressor was not operating was not evident by simple visual observation, unless one observed the unit continuously for 30 min or more and could note that the unit did not shut off during that period of time.

ARBI notified WVCP field service personnel and the installing plumber of the problems, and soon the equipment manufacturer was also brought in to assess the situation. An A.O. Smith representative inspected the installation in late September and determined that a remote immersion sensor for the heat pump had not been properly installed. A.O. Smith provided the temperature sensor that had initially been installed on the storage tank wall exterior. Subsequent monitoring results showed that the heat pump still did not operate. The A.O. Smith representative then indicated that the tank sensor needed to be relocated to a thermal well inside the storage tank. The system was then set up as per manufacturer recommendations:

- 140°F heat pump upper limit set point (5°F dead band)
- 120°F resistance heat set point in each tank
- 120°F setting on the tempering valve that feeds the recirculation loop.

With this strategy the HPWH becomes the primary heating source with limited electric resistance heating expected. The downside of the high HPWH set point is that higher condensing temperatures will lead to lower heat pump efficiencies. If the set points for both heat pump and storage tank water heaters could be lowered without compromising hot water delivery temperatures, the heat pump would operate at higher efficiencies provided compressor short cycling did not adversely degrade performance.

After the October 2011 recommissioning exercise, the HPWH operated reliably and almost exclusively without the need for electric resistance backup heating through early December 2012. The one problem encountered in that span was a failure of the evaporator fan motor bearings in early July 2012, which was promptly fixed.[5] However, in early December 2012, the HPWH again went offline resulting in all water heating load being satisfied by the electric

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[4] The Crouzet micro logic controller is a custom programmable logic controller that can be configured for different applications.

[5] Although not common, bearings in the fan motors of conventional HVAC equipment do occasionally fail. With a small sample size of units at the West Village project, it is not clear if this was a random occurrence or whether it will be an ongoing problem for the installed units.

resistance water heaters. WVCP staff was notified, but for a variety of reasons[6] the HPWH was not brought back online until the end of January 2013.

Identifying proper HPWH performance without the benefit of the ongoing monitoring was certainly a challenge for the field staff. The West Village experience highlights the need for increased contractor and service personnel training in proper installation and commissioning techniques, especially given that the HPWH technology is not commonly seen in this area. In addition, the vendor must provide a more intuitive user interface to facilitate system troubleshooting. Ideally the manufacturer should provide a simple set of measurements for basic system commissioning, including power (or amperage draw) and HPWH supply and return water temperature. The first phase of 16 student apartment HPWH systems (of which the monitored unit was one) were installed by the plumbing subcontractor. Due to the startup problems associated with Phase I, the second phase of 16 apartments completed in the summer of 2012 were commissioned by an HVAC contractor.[7] Also, the set of 16 units for Phase II construction were all manufactured at an A.O. Smith facility and have had far fewer commissioning and service issues than the Phase I units.

3.2 Full-Load Monitoring Data Performance Trends

Figure 7 through Figure 10 present full-load monitoring data from November 2011 to November 2012 to provide a simplified comparison of observed system performance relative to nominal equipment ratings. The manufacturer's data specification lists heating capacity and total heat pump power at four outdoor temperatures (25°, 45°, 65°, and 85°F)[8] at an assumed fixed inlet water temperature of 100°F and a heat pump circulating flow rate of 25 gpm. For comparison, the full-load field monitoring data indicate an average inlet water temperature of 125.4°F and a heat pump flow rate 19.6 gpm. The lack of manufacturer's data at any other flow rate and the observed 20% flow discrepancy make any direct comparisons tenuous at best.

Figure 7 presents heating capacity data as a function of outdoor air dry bulb temperature. The monitored data show the expected trend of increasing heating capacity as outdoor temperatures rise. Outdoor temperature is used as the dependent variable as opposed to outdoor wet bulb temperature to highlight the HPWH's system control strategy, which lowers the evaporator fan speed above 85°F to avoid excessive condensing pressures. The plotted manufacturer's data indicate ~10%–20% higher HPWH capacity than observed, although the manufacturer's reported data assume a return water temperature of 100°F and a flow rate of 25 gpm, both of which were more favorable than what was observed in the field.

Figure 8 plots monitored HPWH electrical demand as a function of both outdoor air dry and wet bulb temperature, as well as the manufacturer's demand data at the four rating points. The manufacturer's data are approximately 10%–20% higher than the monitored data. The monitored full-load data were at an average heat pump inlet water temperature 25°F warmer than the manufacturer's rating point. Another factor that was identified during the data evaluation was the definition of 15-minute continuous operation as defining steady-state HPWH operation. With

[6] Including the upcoming holidays and campus winter break, other maintenance priorities, and development of a plan to upgrade the capabilities and tools available for HPWH diagnostics and servicing.

[7] The initial 16 units installed during Phase I construction represent a manufacturing transition as A.O. Smith had just purchased ETECH. This created some logistical issues on the equipment delivery side.

[8] With 50% RH.

this definition, steady state could be as short as 15 min or considerably longer.[9] With HPWH startup operation affecting performance for 5 min or more, variations in the 15-min interval HPWH demand are to be expected. Figure 9 plots HPWH steady-state demand as a function of inlet water temperature to the unit. These data are better correlated and suggest an approximate 0.4 kW increase in HPWH demand for every 10°F increase in inlet water temperature.

Figure 10 plots full-load monitored COP as a function of outdoor temperature. Monitoring data are fairly well correlated and the resulting full-load COPs match well with the manufacturer's data.

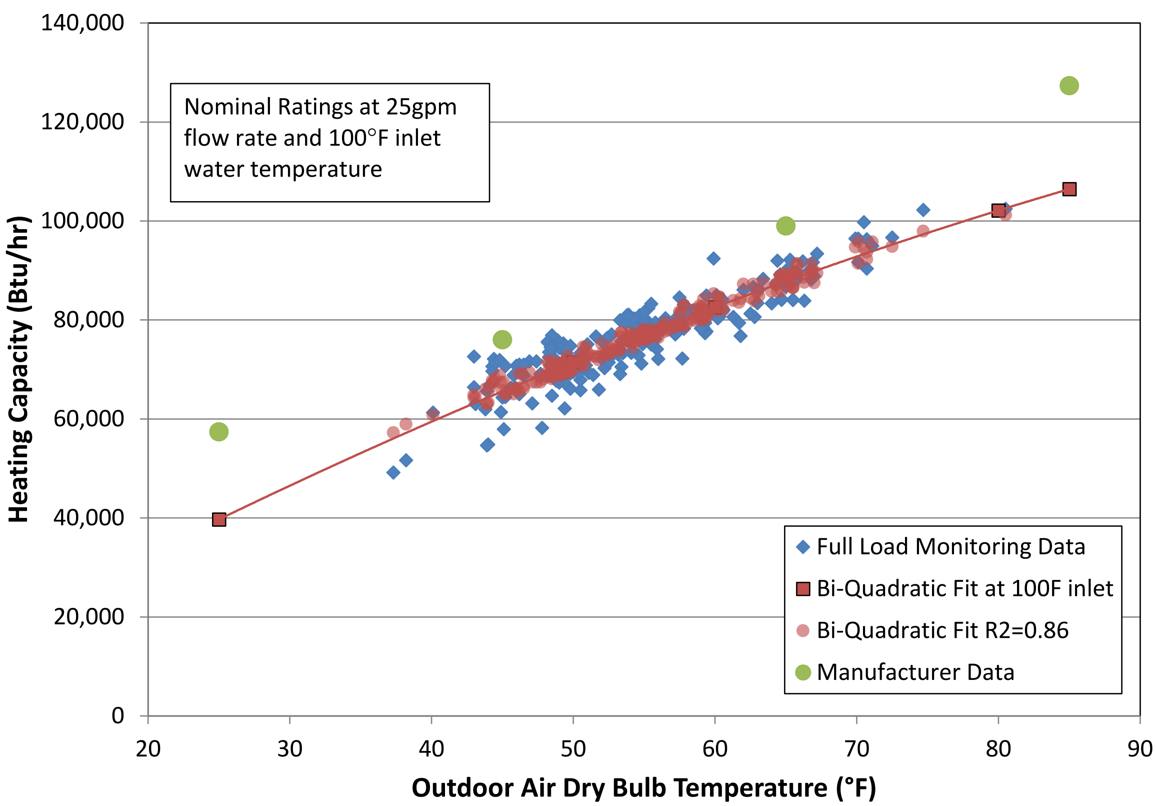

Figure 7. Full-load heating capacity as a function of outdoor dry bulb temperature

[9] The 15-min interval logging reported the fraction of the interval when the compressor was operating. It is therefore difficult to know for certain whether two adjacent monitoring intervals represent continuous operation or two operating cycles.

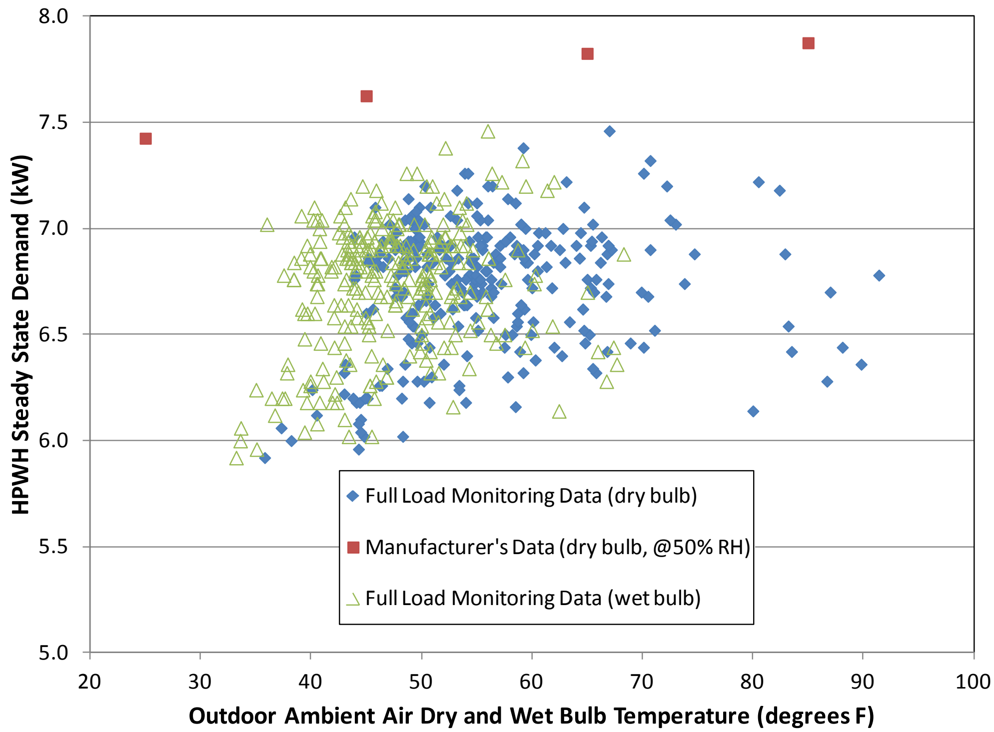

Figure 8. Full-load HPWH demand as a function of outdoor dry and wet bulb temperature

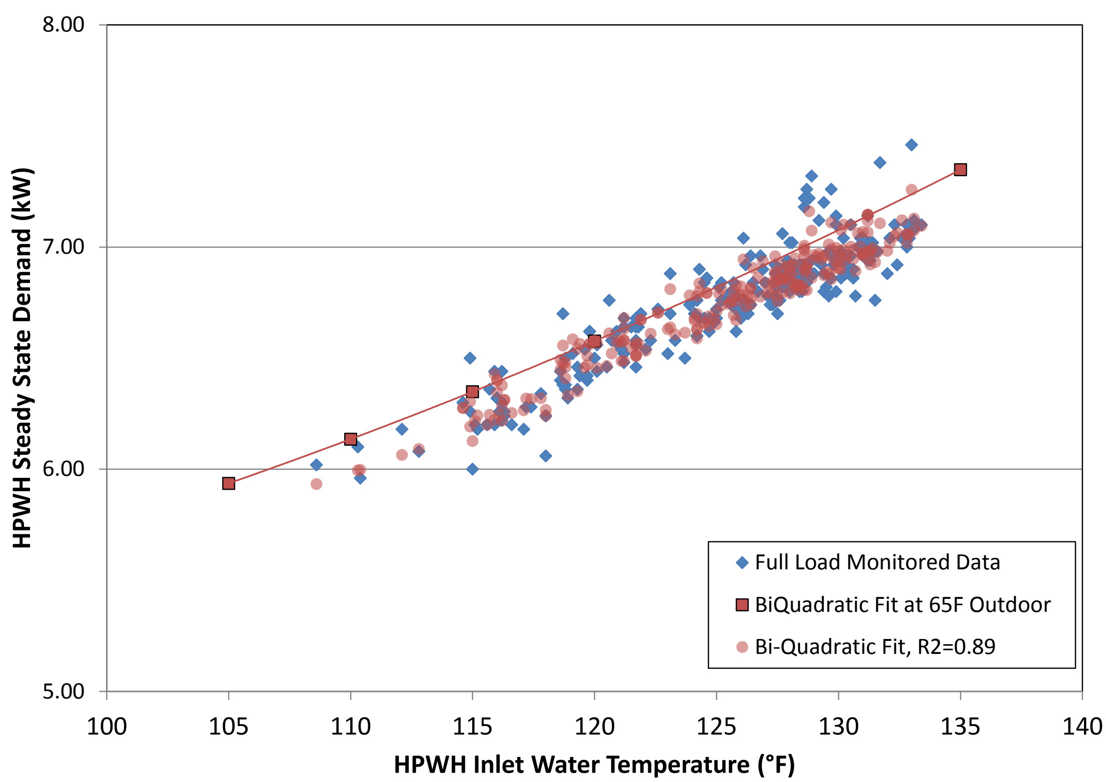

Figure 9. Full-load HPWH demand as a function of inlet water temperature

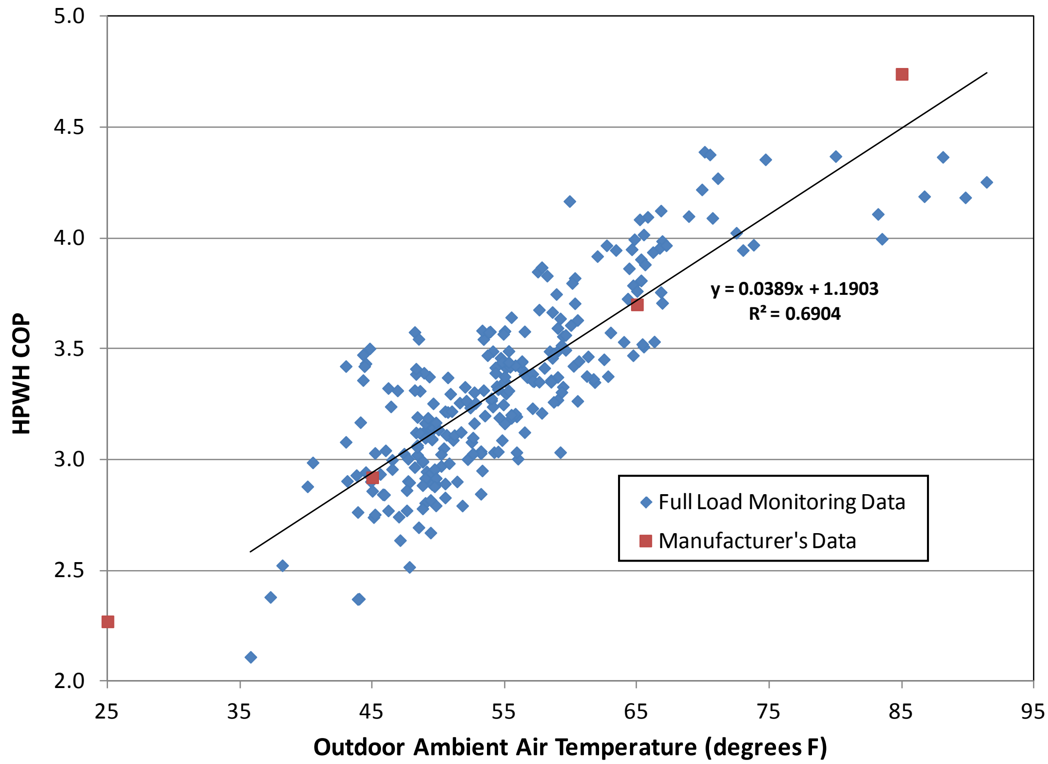

Figure 10. Full-load HPWH COP as a function of outdoor dry bulb temperature

3.3 Developing a Heat Pump Water Heater Performance Map

A multiple linear regression analysis was completed to develop a bi-quadratic relationship between heat pump power and capacity to outdoor dry bulb temperature and leaving water temperature. The performance relationship was developed relative to entering water temperature and outdoor air dry bulb temperature, as shown in Equations 3 and 4 below:

$$\boldsymbol{Pwr_H = a + b(EWT) + c(EWT^2) + \mathrm{d}(\mathrm{OAD}) + \mathrm{e}(\mathrm{OAD}^2) + \mathrm{f}(\mathrm{EWT} * \mathrm{OAD})} \quad (3)$$

$$\boldsymbol{Cap_H = a + b(EWT) + c(EWT^2) + \mathrm{d}(\mathrm{OAD}) + \mathrm{e}(\mathrm{OAD}^2) + \mathrm{f}(\mathrm{EWT} * \mathrm{OAD})} \quad (4)$$

where,

Pwr_H = HPWH power (kW)

Cap_H = HPWH heating capacity (Btu/h)

EWT = HPWH entering water temperature (°F)

OAD = Outdoor air dry bulb temperature (°F)

The Excel ***linest*** function was used to derive the regression coefficients based on full-load monitoring data only. The sample size fitting this criterion was 393 data points, or a total of 98 h. As seen in Figure 7 and Figure 9, the bi-quadratic regression coefficients shown in Table 5 best approximated system performance at full-load. The degree-of-freedom adjusted R-square statistics[10] for power and capacity were 0.89 and 0.86, respectively, where values closer to 1 indicate a high goodness-of-fit. The regression relationships were used to create an input performance map for model interpolation. The map was generated within only the observable range of data; therefore, the model requires extrapolation beyond the range of observed outdoor dry bulb and entering water temperatures.

Table 5. Coefficients for the Bi-Quadratic Functions Relating Capacity and Power

Coefficient	Capacity	Power
a	21,738	5.64
b	(326.47)	(0.0323)
c	1.36766	0.00029
d	2,196.33	(0.0069)
e	(4.5235)	(0.00002)
f	(4.6923)	0.00015

3.4 Heat Pump Water Heater Performance Characteristics

Figure 11 plots daily total hot water usage and heat pump energy delivered on the primary Y-axis, and daily HPWH and electric resistance kWh on the secondary Y-axis. Hot water loads peak during the January/February time frame and are lowest during midsummer (when apartments are not fully occupied and loads are naturally lower) and during breaks in the academic year (Thanksgiving, winter holidays, and spring break). The range in daily loads is high with day-to-day variations of 2:1 and seasonal variations of 7 to 10:1 not uncommon. Average HPWH energy usage until December 2012 averaged about 37 kWh/day, with supplemental electric resistance use during that period only totaling about 1% of total annual consumption. In early December 2012, the HPWH went down again and electricity consumption spiked to more than 100 kWh/day. After the HPWH was brought back online in late January 2013, the supplemental electricity usage (bottom right of graph) dropped back to levels consistent with January 2012. The fact that supplemental electric use was minimal during "normal" system operation, suggests that the sizing of the storage tanks and selected set points are appropriate for minimizing resistance heat given the observed loads for this building.[11]

Figure 12 plots daily monitored thermal energy delivered as a function of the total energy consumed by the water heating system. Thermal energy delivered is defined as the sum of the HPWH and any supplemental resistance electric water heating. The majority of the data (blue symbols) represent operation when the HPWH was operational,[12] while the red symbols indicate days when water heating loads were met by electric resistance operation. The wide range of thermal energy delivered to storage, varying from about 60 to 450 kBtu/day, reflects the expected seasonal variations in occupancy due to academic housing, day-to-day usage variations,

[10] R^2=1-SSE(n-1)/SST(v) where SSE is the sum of the squares of error between observed and predicted values, SST is the sum of the squares of error between observed value and the predicted mean, n is the number of observed full-load data and v is the difference in observed data and regression coefficients.

[11] It should be noted that the monitored HPWH was on a building with five four-bedroom apartments and six two-bedroom units (one additional four-bedroom unit served as the unoccupied "model home" unit) for a total of 32 occupants. Other buildings have six three and six four-bedroom units, totaling 42 occupants. This 31% higher occupant density would likely result in significantly higher supplemental heat use.

[12] For the periods when HPWH was operational, electric resistance amounted to 1.1% of total water heating use.

and seasonal climatic influences on hot water demand. For "typical" usage levels of around 300 kBtu/day, the all-electric resistance water heating consumed about 2.5 times as much energy as the HPWH.

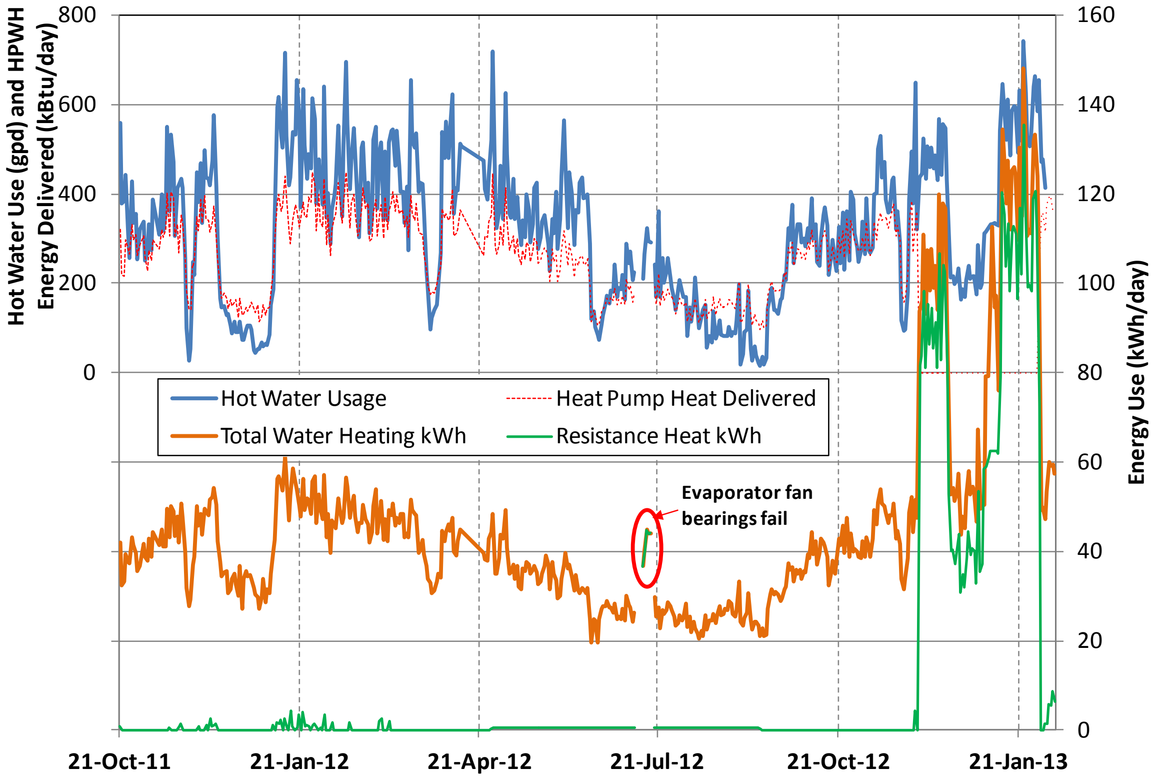

Figure 11. Daily hot water loads, HPWH energy delivered, and energy consumption

Figure 13 compiles the monitored data on a monthly basis. Daily per-capita hot water use and per-apartment electricity use are plotted on the primary Y-axis and the monthly average system COP is plotted on the secondary Y-axis. Hot water usage and resulting energy use peaks in the winter months (note that for December 2012 and January 2013, usage is purely electric resistance). For months where the HPWH was operating, COPs ranged from 2.0 to 2.3, with the unexpected exception of the warmest summer months when COPs fell to the 1.7 to 1.9 range. An average COP of 2.12 was monitored over the November 2011 through October 2012 period.

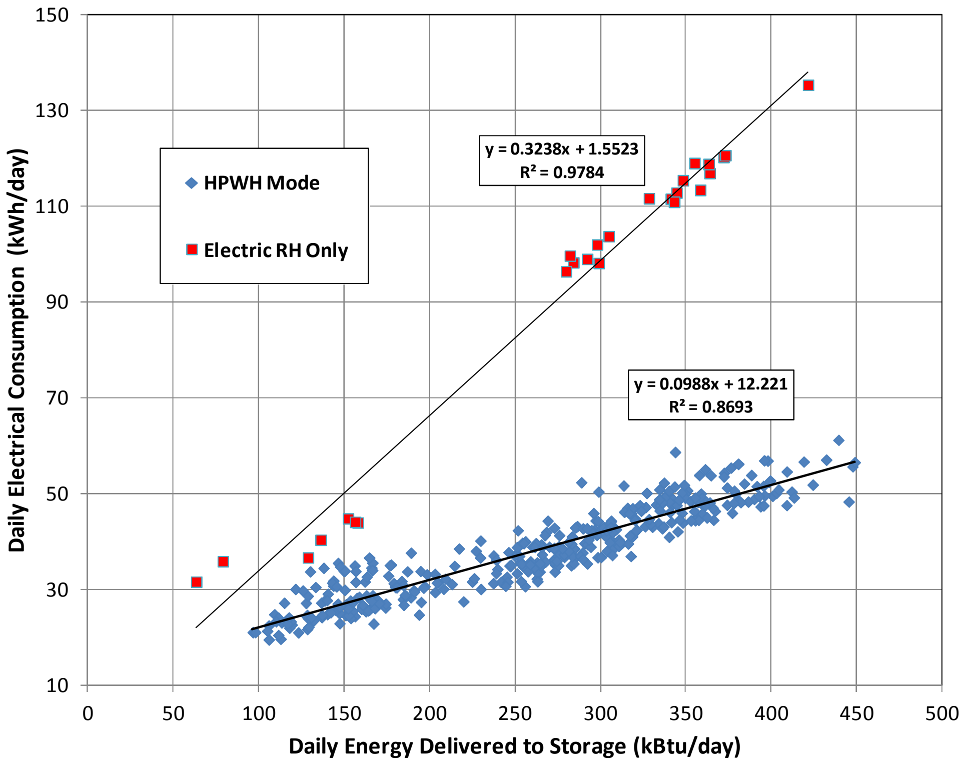

Figure 12. Comparison of daily water heating energy use versus thermal output

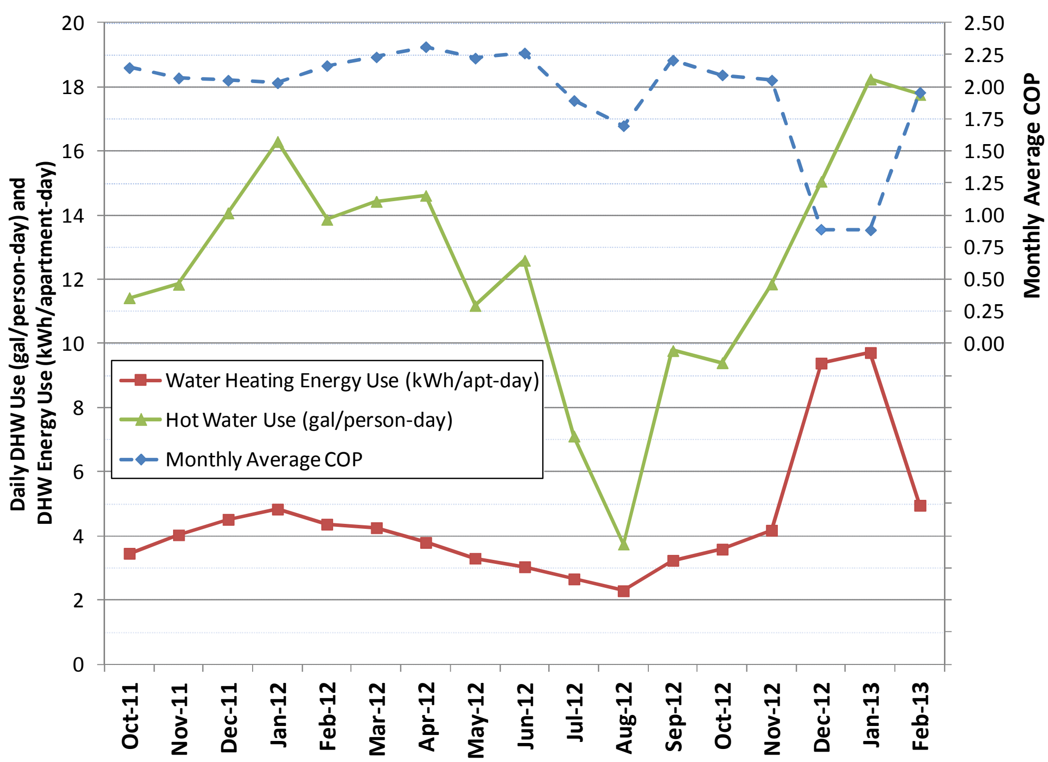

Figure 13. Monthly system performance summary

The reason for the summer efficiency degradation is counterintuitive, since one would expect that efficiencies would be highest during the warmest months. One factor affecting summer performance is high standby energy consumption. With low summer water heating loads, standby energy becomes a greater fraction of the energy consumed. The HPWH was found to average about 450 W of standby energy usage due to pipe heaters, crankcase heaters, and controls.[13] In addition, every heat pump cycle begins with a 2-min fan and pump operating cycle before the compressor is energized. This draws slightly more than 1 kW and represents a thermal loss as heated water from the storage tank is circulated to the outdoor HPWH. Short summer operating cycles would experience this additional performance degradation to a greater extent than winter cycles when the loads are higher, heating capacity is lower, and the resulting cycle times are longer. This effect is highlighted in Figure 14, which plots the patterns of HPWH operation over the course of 3 full weeks: a midwinter week, an early fall week, and a midsummer week (when occupancy and loads are low). The Y-axis presents the HPWH run fraction over the 15-min period and the X-axis represents all the data sorted from no operation to highest run fraction. In the winter week only about of the 10% of the 15-min operating intervals had no heat pump operation, while the summer week showed about 55% of the intervals without any heat pump operation. Looking only at intervals when the heat pump operated for some fraction of the 15-min period, the mean runtime ranged from 30% during the winter, to 24% during the fall, and 17% in the summer. The two key performance factors to highlight in Figure 14 are the seasonality of HPWH runtime during the course of the year and the implication of short-cycling on overall system performance. The effect of short-cycling on system performance has been noted in other work (Gray 2010).

At the end of the field monitoring work, short-term 1-min interval logging was implemented to better observe the startup characteristics of the unit. Results show that that it would typically take 8–10 min for the HPWH to achieve a steady-state capacity situation (defined as where the supply to return water temperature differential remains relatively constant). Given that there were only about 400 monitoring points defined as full-load operation, this suggests that improved performance could be realized by lengthening the average duty cycle. Several strategies to achieve this include providing additional storage volume in the HPWH tank, increasing the storage tank temperature differential that controls the system's operation, and utilizing a multistage or variable speed compressor. To evaluate the potential of reducing short-cycling, several additional TRNSYS runs were completed looking at additional storage volume and a larger storage tank temperature dead band, which allows for the HPWH to run longer cycles. Increasing the storage volume (and the associated tank losses) of the two tanks from 120 to 150 gal was found to reduce annual Sacramento electricity consumption by 1.2%. Increasing the storage tank dead band from 5° to 10°F further reduced total water heating energy use by 0.7% despite the amount of resistance heat increasing with the wider dead band. Further lab and field study in this area is warranted to better assess performance impacts.

[13] Ranging from ~ 250 Watts at 100°F ambient temperature to nearly 600 Watts at 40°F.

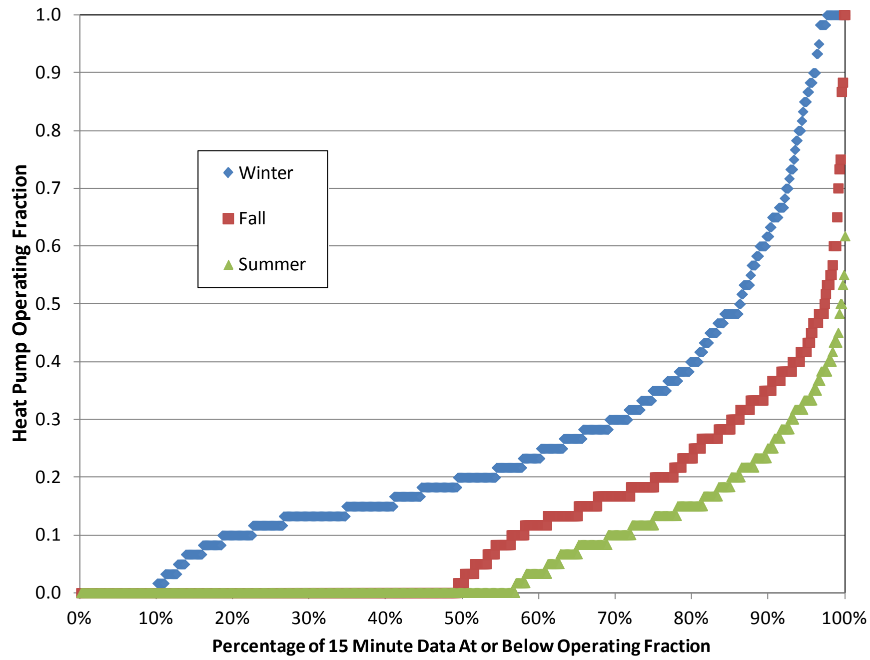

Figure 14. Seasonal characterization of heat pump operation during typical weeks

The reduction in summer loads is due not only to lower student occupancy, but also to the impact of cold water inlet temperature seasonal variations, which affects both the energy needed to heat the incoming water up to set point, as well as the required ratio of hot and cold mixing for uses such as showers. Figure 15 plots daily average cold water temperature during the course of the monitoring. Data are filtered for 15-min periods with more than 10 gal of recorded hot water usage to provide greater confidence that the surface mounted cold water thermocouple is providing a representative reading of the pipe surface temperature.[14] Hot water load seasonality due to higher than assumed seasonal fluctuations in water heater inlet temperature is an effect that impacts both hot water use and system efficiency.

[14] During time periods when the university is not open for instruction (i.e., winter and spring breaks), the average daily cold water temperature becomes more erratic.

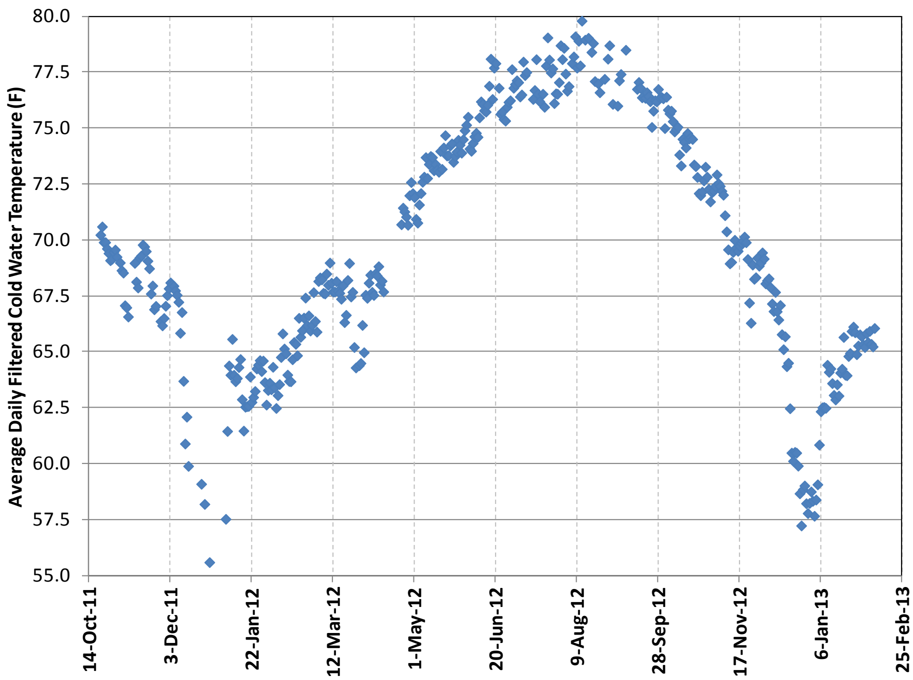

Figure 15. Average daily filtered cold water inlet temperature

3.5 TRNSYS Model Validation Efforts

The performance map was developed using the 15-min full-load monitored data from November 2011 through November 2012. The available full-load data resulted in a performance map that was valid for entering water temperatures ranging from 110°–135°F and outdoor air temperatures of 35°–95°F. While the monitoring data were logged at a 15-minute resolution, it was necessary to run the model at a 15-second time step to capture the transient effects inherent in the controls.

The model acts by performing a table lookup to determine heating capacity and power, and therefore is only able to simulate steady-state performance. (Due to the relative size of the storage tanks, and the observed hot water loads, the heat pump operated at full steady-state conditions for fewer than 1% of all the collected monitoring data.) In order to approximate system startup performance, where the capacity and electricity demand are low as the system builds to full operating conditions, a second "startup" heat pump model was developed with a lower rated capacity (50% of nominal). Program logic controls were added to run this heat pump for the first 3 min of any operating cycling, at which point the model transitions to the steady-state performance model. Although this approach is not ideal, the limitations of the TRNSYS steady-state model required some adjustments to better mimic observed performance.

A similar technique was applied when the HPWH senses outdoor temperatures lower than 40°F and lowers the heating set point to 125°F. A diagram of the entire system, including the three representative heat pumps, is shown in Figure 16. The evaporator fan was a two-speed fan programmed to drop into low speed when outdoor temperatures are higher than 85°F to avoid an overcapacity situation. The TRNSYS model also makes the evaporator fan speed, and airflow fixed parameters read only at model initialization. Using the built-in calculator function, the effect was modeled and added to the simulated heat pump power.

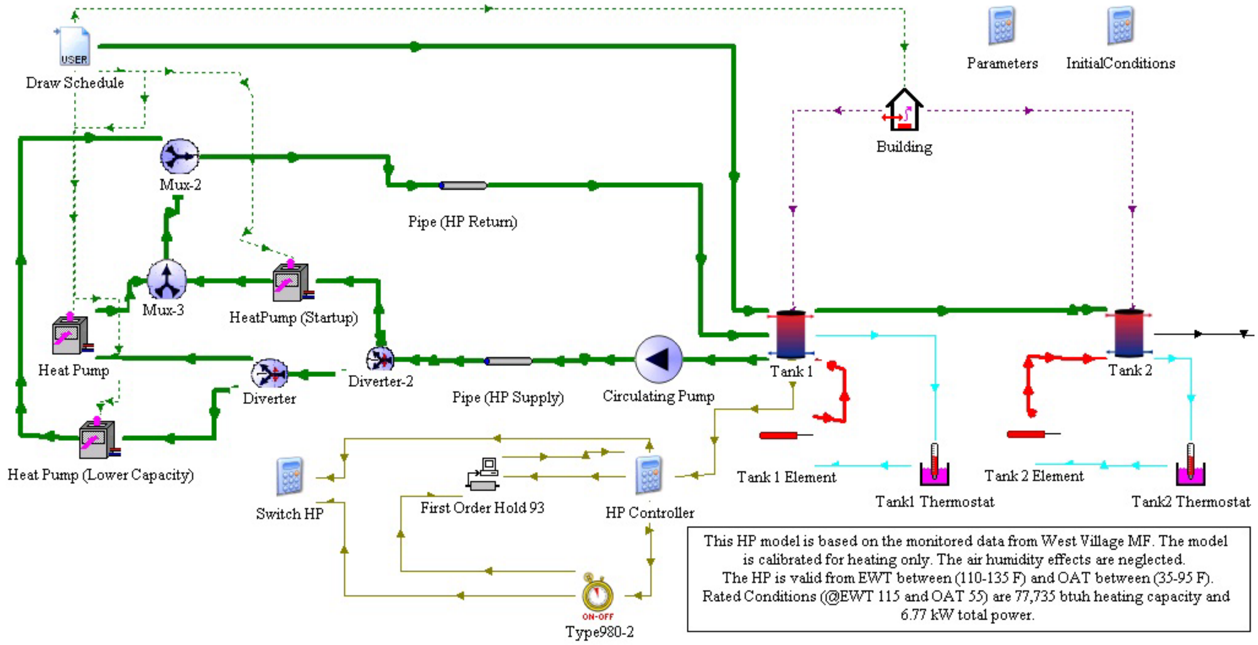

Figure 16. TRNSYS HPWH model configuration

Despite the many embedded thermostat options in TRNSYS, the program lacked a thermostat that had both dead band parameters and a minimum compressor runtime. Using the built-in calculator function, a controller was developed that modeled the control logic of the heat pump, where the on-temperature was 135°F, off 140°F, with a minimum compressor runtime of 4 min. In Figure 16, a time delay model (Type 93) was used to carry state information into the next cycle (first order hold), and the runtime calculator (Type 980) was used to integrate control status.

Finally, the unit is set to go into a defrost cycle, where heat from the circulated storage tank water is used to remove frost or ice from the evaporator coils at low outdoor conditions. This effect was not observed in the field in the mild Davis, California climate, and was therefore difficult to model without an available performance map. To approximate this effect, any simulation time steps where outdoor temperatures were lower than freezing (32°F), the compressor was modeled as “off” with supplemental resistance heat used for DHW, as needed. This effect was necessary in modeling HPWH performance in the colder U.S. climates.

Two sample weeks’ worth of monitored data were used to drive the model for the validation exercise: a winter week from February 1–7, 2013 and a fall week from October 9–21, 2012. Given that the model responds to “smoothed” hot water loads (i.e., uniform hot water loads over a full 15-min period), a direct comparison of model and monitored results on a short time step was problematic. Table 6 provides a summary of energy use and thermal energy delivered over each of the 2 weeks. In the winter, the model was found to slightly overestimate heat pump usage and slightly underestimate electric element usage, while overpredicting heat pump thermal contribution by about 12%. During the fall, the heat pump was able to provide 100% of the load, and the model provides a good match to the monitored data.

Table 6. Model Validation Results Over Typical Winter and Fall 7-Day Period

	Heat Pump Energy Use (kWh)	Electric Element Energy Use (kWh)	Heat Pump Energy Delivered (kBtu)	Hot Water Demand (kBtu)
Winter—Monitored Data	355	23	2,543	2,197
Winter—TRNSYS Model	365	20	2,849	2,182
Fall—Monitored Data	284	–	2,007	1,178
Fall—TRNSYS Model	282	–	1,913	1,188

Several adjustments to the model were completed to develop the results shown in Table 6. The mechanical room housing the storage tanks was modeled as a 540-ft^2 room, with a thermal capacitance of 2,105 Btu/°F and a heat transfer coefficient to outdoors of 23.26 Btu/(h-°F). This assumption provided a reasonable alignment with seasonal mechanical room temperatures.[15]

The HPWH thermostat location was observed to be midway between the supply and return port locations on the first tank, roughly at the tank midpoint. In order to better align the data, the location for the electric element was moved one node higher (so that some mixing with the tank would occur after the heat pump supply). The electric element location, however, was assumed to be at the bottom node of the tank, to give time for adequate mixing before supply.

3.6 Projected Performance in Different Climates

The validated model was run through a series of different climates, with climate-adjusted hot water loads. In addition to the HPWH case, conventional all-electric and gas storage cases were simulated with TRNSYS for comparison. For the natural gas option, the two storage water heaters were modeled with an input rating of 309 kBtu/h and a thermal efficiency of 80%. The draw profile supplied to the simulation was acquired from ASHRAE service water heating guidelines. To account for typical recirculation losses, the hourly fixture end usage was increased by 30%.

Table 7 shows the annual performance of the heat pump in the climates of Phoenix, Houston, Sacramento, Seattle, Denver, and Chicago. Typically in hot and mild climates, the HPWH is projected to achieve annual COPs above 2.0. In the colder climates, such as Denver and Chicago, the HPWH is unable to fully meet the load. In addition, at outdoor temperatures below 32°F, the compressor was locked out and all heating was provided by electric resistance. The water heating loads are also up to 30% higher in these climates relative to the warmer climates, which also accounts for the higher resistance heat and heat pump use. The water heating energy delivered with the HPWH configuration is slightly higher in warmer climates due to the fact that the heat

[15] Mechanical room temperatures were not monitored.

pump supplies 140°F water to the storage tank, while the thermostats in the conventional base case runs were set to 135°F to better align with average delivery temperatures. The supplemental electric resistance elements in the heat pump configuration were set to 120°F; therefore, in colder climates, where the unit relies more heavily on resistance heating, the delivered water heater energy is lower.

Table 7. HPWH, Electric, and Gas Water Heater Performance Comparison in Selected Climates

	Phoenix	Houston	Sacramento	Seattle	Denver	Chicago
HPWH (140°F Heat Pump Set Point, 120°F Backup)						
Heat Pump Energy Input (kWh/year)	14,692	16,385	17,850	18,838	15,628	15,185
Electric Resistance Energy Use (kWh/year)	–	–	275	1,150	8,161	10,562
Water Heating Energy Delivered (kBtu/year)	104,715	117,475	129,561	146,575	143,338	145,876
Annual System COP	2.09	2.10	2.09	2.15	1.77	1.66
Electric Resistance Storage (135°F Set Point)						
Electric Resistance Energy Use (kWh/year)	32,020	36,043	41,636	49,208	49,616	50,777
Water Heating Energy Delivered (kBtu/year)	97,336	110,181	127,479	151,882	153,164	156,823
Water Heating Efficiency	89%	90%	90%	90%	90%	90%
HPWH kWh Savings Versus Electricity	54%	55%	56%	59%	52%	49%
Natural Gas (135°F Set Point)						
Natural Gas Use (therms/year)	1,363	1,534	1,773	2,095	2,112	2,162
Water Heating Energy Delivered (kBtu/year)	97,213	110,044	127,333	151,721	153,009	156,666
Water Heating Efficiency	71%	72%	72%	72%	72%	72%

The HPWH simulations were projected save 49%–59% electrical energy savings relative to the electricity base case. Figure 17 shows the comparison in annual operating costs for each option given the assumed utility rates. HPWH operating costs and overall economics are sensitive to factors including utility rates, climate, system plumbing configuration, storage tank sizing, hot water load magnitude, and operating set points. Performance sensitivity to these site-specific factors was observed both in this study and reported in prior field monitoring efforts (Gray 2010).

A more generic look at HPWH economics confirms that relative to natural gas water heating, HPWHs face a challenging prospect with the low natural gas rates currently found in much of the country. A simplistic method to provide a first cut assessment of HPWH viability based on local utility rates is shown in Figure 18. The graph shows the maximum average electricity rate that would result in operating cost neutrality at a given local natural gas rate and assumed HPWH operating efficiency. An example case with natural gas at $1.10/therm and average electricity rates of $0.14/kWh suggests that annual performance greater than a 2.5 COP is needed for the HPWH to offer any operating cost advantage. Current performance expectations suggest that COPs of 2–2.5 are readily achievable, with higher efficiencies possible in applications that provide for favorable operating conditions and extended operating cycles.

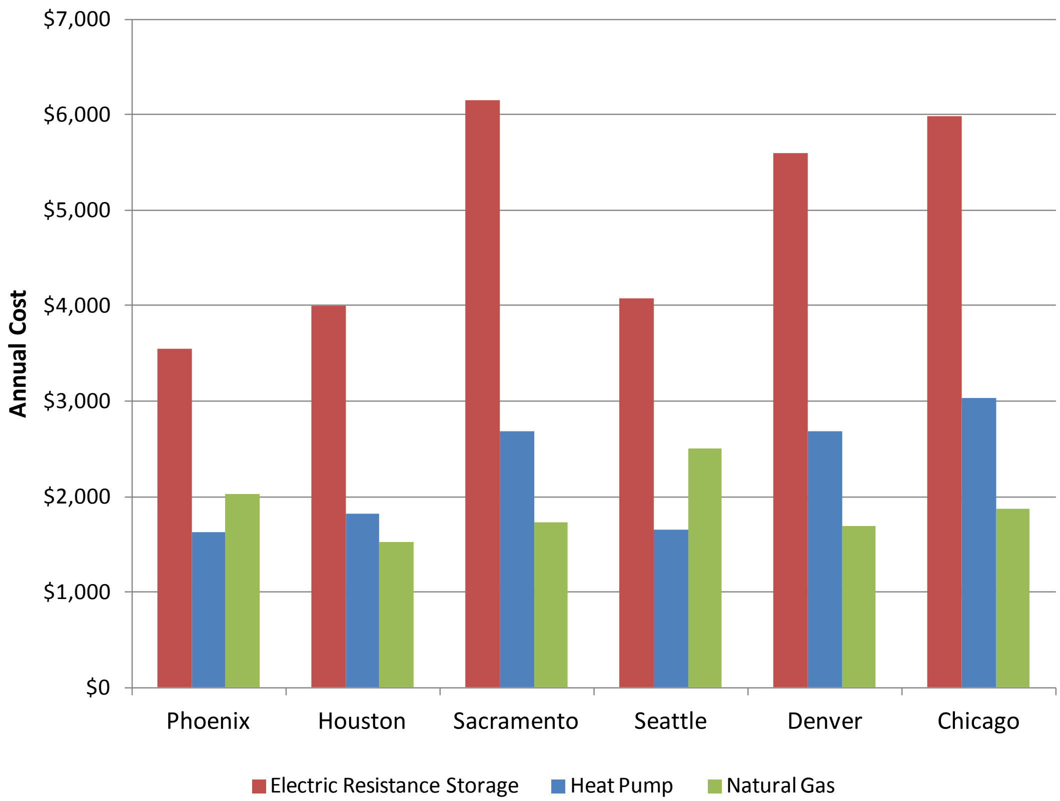

Figure 17. Projected annual operating cost comparison in selected climates

Overall HPWH cost effectiveness is dependent on both on operating cost savings and incremental cost. The installed cost for the A.O. Smith HPWH was $22,300. Relative to an electric resistance base case system, the incremental HPWH cost is about $20,000. The central gas base case is more difficult to estimate, since the cost of bringing natural gas to the site (especially if the application is all-electric, as implemented at West Village) can be significant. For this application, we are assuming a $10,000 incremental HPWH cost relative to central gas water heating. With TRNSYS projected annual savings versus electric water heating of $1,920–$3,475/year, simple paybacks of 5.8–10.4 years are projected. To achieve similar paybacks relative to gas water heating, annual savings of $960–$1,720 are needed. Achieving this level of savings in many parts of the country is currently difficult, although there are several states (e.g., Georgia, North Carolina, Alabama, Florida, and Hawaii) where the relative costs of electricity to natural gas are more favorable.[16]

[16] http://www.eia.gov/dnav/ng/NG_SUM_LSUM_A_EPG0_PRS_DMCF_M.htm and

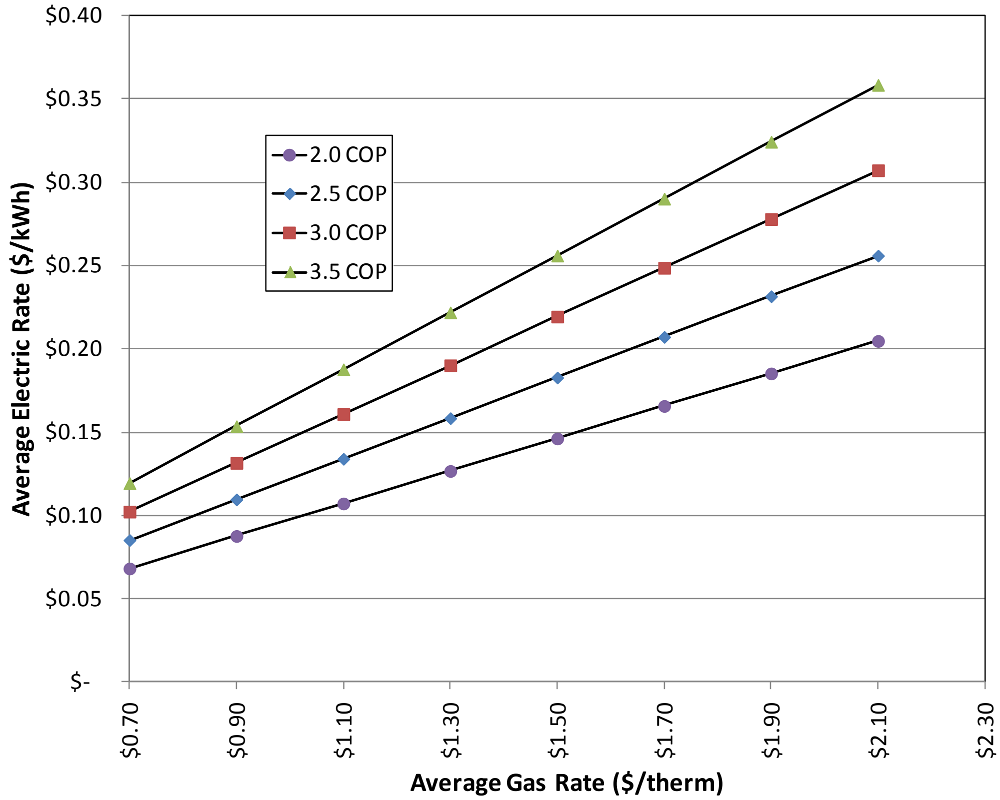

Figure 18. HPWH breakeven costs as a function of COP and utility rates

http://www.eia.gov/electricity/monthly/epm_table_grapher.cfm?t=epmt_5_6_b

4 Conclusions

This research effort focused on the monitoring and evaluation of a central HPWH installed in student apartments at the University of California-Davis campus. The evaluation process including validating a TRNSYS air-to-water heat pump model with the field data and using the model to provide an initial comparison of multifamily HPWH performance in six U.S. climates with varying utility rates.

The primary research questions addressed include:

1. What are the measured performance and reliability of the central HPWH and how do these compare to expectations from modeling and manufacturer claims?

The manufacturer's performance ratings for the A.O. Smith E-Tech WH115-HTC are based on steady-state operation at a flow rate of 25 gpm and an inlet water temperature of 100ºF. Field monitoring indicated an actual flow rate of 20 gpm with inlet water temperatures well above 100°F due to the plumbing configuration, which resulted in recirculation return water being mixed with the cold water supply. In addition, the sizing of the storage and the programmed temperature dead band resulted in limited steady-state operation. Although overall steady-state COPs in the 3.0 to 4.0 range were in line with the manufacturer's data, high standby parasitics and frequent short-cycling degraded the annual COP to 2.12. A multistage HPWH would likely demonstrate improved efficiencies by extending the average compressor run cycle length. Another strategy to extend cycle times would be a more sophisticated control algorithm to allow for a larger dead band or overcharging of storage by 5°–10°F, if the system has not run for a minimum amount of time. Preliminary modeling efforts suggest this might amount to a 2% reduction in annual electricity consumption, but more evaluation is needed to better document performance.

The installed HPWH was found to operate reliably over the course of the 16-month period. Startup problems in Phase I due to improper installation and commissioning were not observed in Phase II as the installers gained experience with the technology. The one reliability concern experienced with the monitored unit was the need to replace the evaporator fan motor in July 2012, due to bearing failures. This apparently happened at one of the other 15 units installed in Phase I. Longer term reliability of the units and associated maintenance costs need to be studied to better understand life cycle economics.

2. How viable is the central HPWH system compared to other conventional options under varying retail rate scenarios?

HPWHs will provide significant electricity savings relative to electric resistance water heaters with TRNSYS projected savings ranging from 49%–59% based on climate impacts. TRNSYS projected annual savings versus electric water heating of $1,920–$3,475/year results in simple paybacks in the range of 6–10 years for the cases evaluated. If natural gas is available, the economics are generally not favorable as long as natural gas rates are low (~$1/therm). Some Southeastern states and Hawaii may have favorable HPWH economics due to high gas rates relative to electricity. Opportunities for improved performance should exist by optimizing system performance to limit compressor short cycling and avoiding high HPWH inlet water temperatures (improving efficiencies). Current HPWH equipment costs are high and would benefit from increased market demand and competition in the marketplace.

3. Under what load and ambient conditions does the HPWH fail to meet the load and how frequently does this occur?

Under the conditions observed at the University of California-Davis West Village project, the monitored HPWH used very little supplemental heating (1.1% of annual water heating electricity use) when the HPWH was operating properly. This suggests that the sizing of the unit and the supplemental storage is appropriate for the building application (six two-bedroom and six four-bedroom units). Since the monitored configuration served only 32 occupants,[17] more heavily loaded units would tend to experience more supplemental electricity use. Situations where supplemental heat was needed were limited to midwinter conditions with low ambient air temperatures (< 45°F) and an average hot water demand of 3 gpm over a 30-min period or longer.

4. How does the HPWH sizing to peak load ratio compare to typical single family applications and what are the performance implications?

The 10.5-ton nominal HPWH with 240 gal of storage was sized to meet the hot water loads of a building with 42 occupants. The 2,500 Btu/h compressor capacity per person is consistent with a typical single family residential HPWH (6,000–8,000 Btu/h for a typical family size of three), but the 6 gal of storage per person is considerably less than the 15–20 gal common to the single-family HPWH. The greater diversity in hot water loads observed with the multifamily application resulted in much less resistance heat consumption than has typically been reported in prior single family HPWH research (Amarnath and Bush 2012). However, short-cycling of the compressor resulted in much lower seasonal efficiencies than observed in the full-load data. Optimization of storage sizing and control set points, and potentially the introduction of multistage compressor should allow the central HPWH to operate at improved efficiencies.

[17] One of the four bedroom units was the unoccupied model unit used for leasing purposes.

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Appendix

The following graphs provide some more detailed results from the TRNSYS modeling validation effort.

In addition to modeling the heat pump performance accurately, it was also critical to capture the temperature dependency of the unit's standby power. For a full week of operation, Figure 19 plots monitored outdoor dry bulb temperature (secondary Y-axis) and monitored HPWH power (blue line). The graph only plots HPWH demand up to 1.0 kW, as it focuses on the standby data around 0.5 kW. The red symbols plot 15-min demand from the TRNSYS validation simulation. The modeled standby varies from slightly 500 Watts during nighttime periods where outdoor temperatures are in the low 50s to 300–350 Watts as temperatures rise above 80°F.

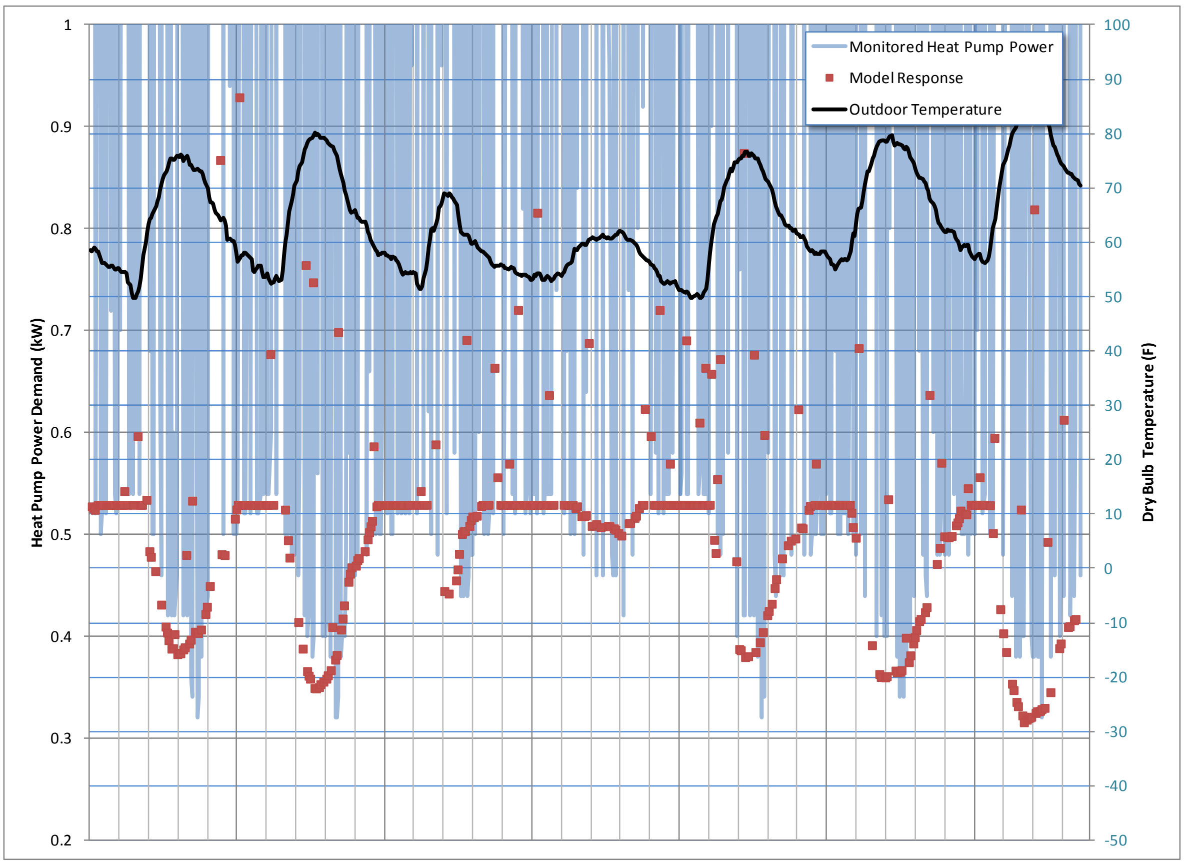

Figure 19. Standby power dependence with air temperature

The heat pump supply and return temperatures reported by the model aligned well with the monitoring data, as seen Figure 20 and Figure 21. In the winter (Figure 20), the heat pump controls reduces its output temperature under low outdoor dry bulb conditions. In the fall, the outdoor dry bulb temperatures remain above the temperature threshold, and the supply and return temperatures remain stable. The return temperature during the fall is, on average, a few degrees warmer than the model prediction. The fall week observed had little full-load operation, and during periods of relaxed operation, the water mixed with the tank and reported higher temperatures. In general, there is greater observed variation with the monitored data as the model relies on smoothed hot water loads over the duration of the 15 min.

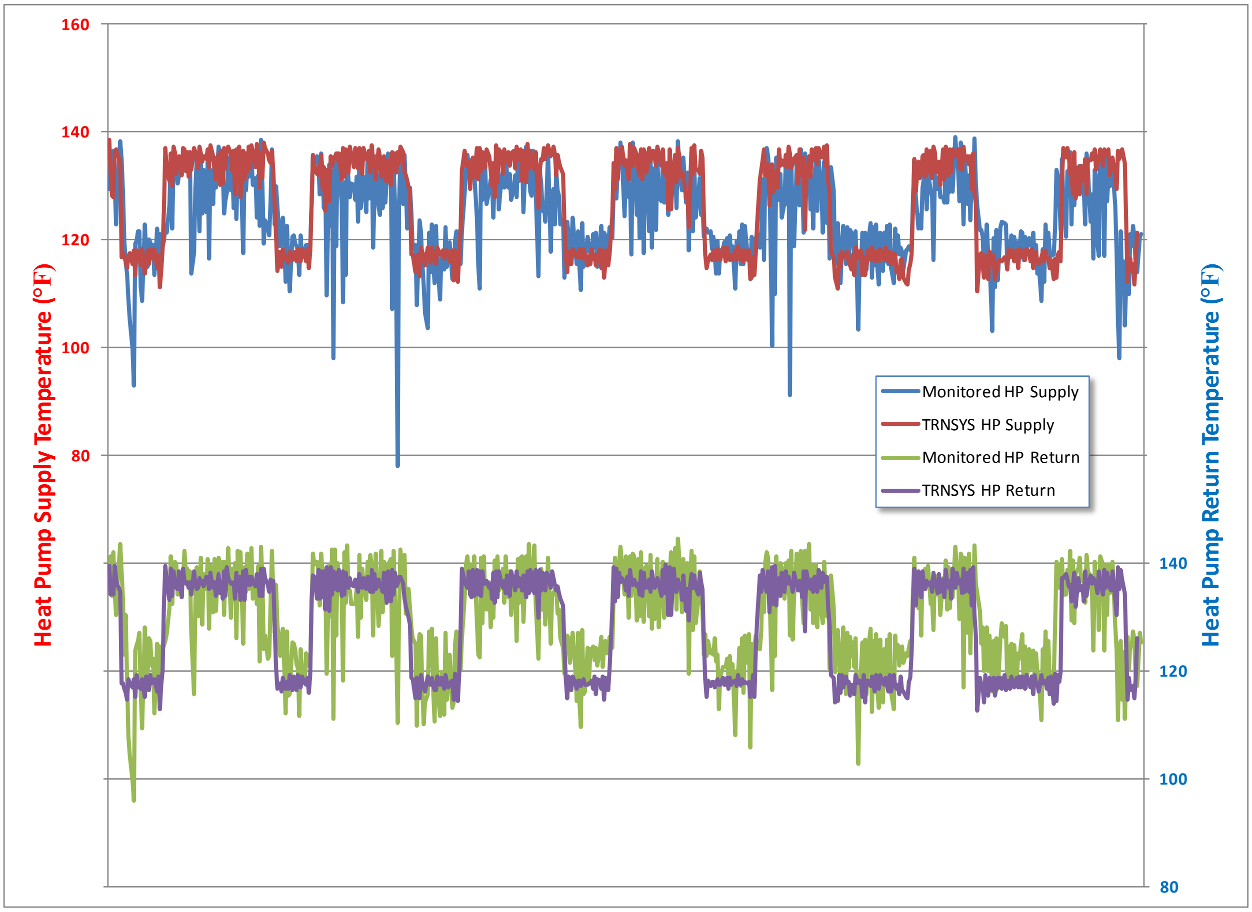

Figure 20. Validation of model performance under typical winter conditions

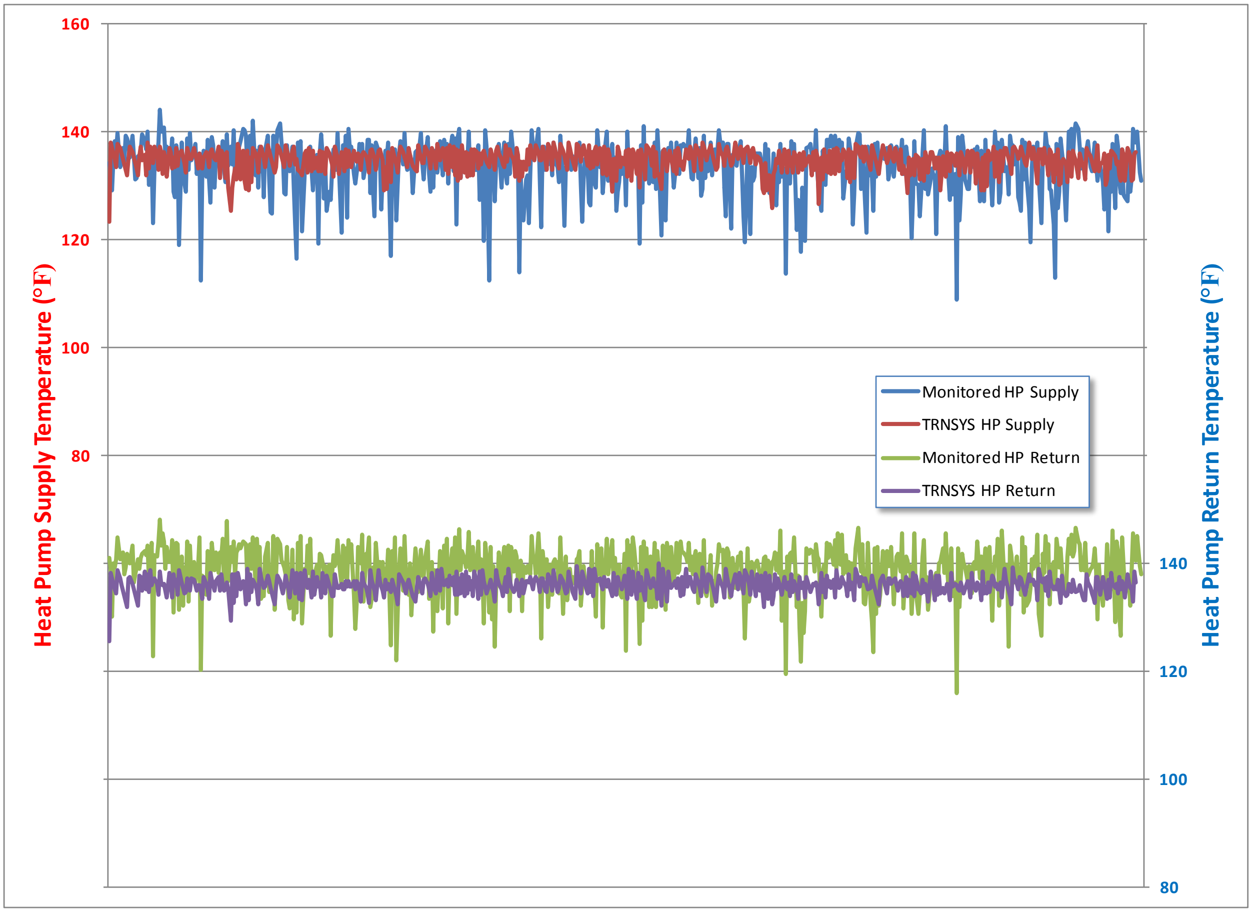

Figure 21. Validation of model performance under typical fall conditions

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