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Washington State University Energy Program

February 2016

Building AMERICA
U.S. Department of Energy

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Prepared for:

The National Renewable Energy Laboratory

On behalf of the U.S. Department of Energy's Building America Program

Office of Energy Efficiency and Renewable Energy

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NREL Contract No. DE-AC36-08GO28308

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WSUEEP15-009

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Prepared under Subcontract No. KNDJ-0-40339-05

February 2016

The work presented in this report does not represent performance of any product relative to regulated minimum efficiency requirements.

The laboratory and/or field sites used for this work are not certified rating test facilities. The conditions and methods under which products were characterized for this work differ from standard rating conditions, as described.

Because the methods and conditions differ, the reported results are not comparable to rated product performance and should only be used to estimate performance under the measured conditions.

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Definitions

AC	Air Conditioning
ACH_{50}	Air changes per hour at 50 Pascals
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BA	Building America
BEopt™	Building Energy Optimization
Btu/h	British thermal units per hour
CFM	Cubic feet per minute
CT	Current transducer
DHP	Ductless heat pump
ER	electric resistance
ESHNW	ENERGY STAR Homes Northwest
FHA	Federal Housing Administration
GPM	Gallons per minute
HFH	Habitat for Humanity
HRV	Heat recovery ventilator
HSPF	Heating Seasonal Performance Factor
HVAC	Heating, ventilating, and air conditioning
IAQ	indoor air quality
IR	Infrared
kWh	kilowatt-hours
kWh/yr	kilowatt-hours per year
kWh/ft^2	kilowatt-hours per square foot
LCCA	Life Cycle Cost Analysis
NREL	National Renewable Energy Laboratory
OAT	Outdoor Air Temperature
PNW	Pacific Northwest
R^2	coefficient of determination
RH	Relative humidity
SEER	Seasonal Energy Efficiency Ratio
ft^2	Square foot, Square Feet
TMY	Typical Meteorological Year
TPU	Tacoma Public Utilities
WSU	Washington State University
XPS	Extruded polystyrene

Acknowledgments

This study was made possible by the interest and collaboration of many organizations and the homeowner participants.

At the Tacoma/Pierce County Habitat for Humanity: Maureen Fife, chief executive officer; Gomer Roseman, director of site development and construction; Guy Nielsen, construction site manager; and Carolyn Benbow, family services coordinator. The Habitat for Humanity homeowner participants allowed the research team to install study instrumentation in their homes, agreed to weekly switching of the heating system in their common living area, and participated in study related surveys. Gomer Roseman provided cost data for the electric resistance heating systems, ductless heat pump (DHP) system, and DHP installation preparation.

At Tacoma Public Utilities: Rich Arneson, Bruce Carter, Cathy Carruthers, Jeremy Stewart, Rachel Clark, Molly Ortiz, and Ying Tang provided project planning, project management, documentation, technical services, and statistical/analytical services.

At the Washington State University Energy Program: Michael Lubliner, Luke Howard, David Hales, and Rick Kunkle provided onsite commissioning of data logger systems, monitoring, data management, documentation, and analysis. Ken Eklund provided administrative assistance. Research and technical support to the project was also provided by the U.S. Department of Energy to Washington State University as a member of the Building America Partnership for Improved Residential Construction.

At Bates Technical College: Dave Leenhouts instructor, and students of the 2013, 2014, and 2015 electrician classes provided electrical wiring design and installation of the electronic time-clock switching system that controlled the living room space heating; they also installed the data logger devices on the 120/240 volt circuits. Leenhouts also provided cost estimates of wiring time and miscellaneous material for typical living room electric resistance zonal heating and for the DHPs.

This project was cofunded by three Washington State electric utilities: Tacoma Public Utilities, Snohomish County Public Utilities Department, and Cowlitz County Public Utilities Deparment. The Bonneville Power Administration provided funding and data logger equipment loans.

Executive Summary

The Washington State University (WSU) Energy Program's Building America (BA) team conducted a case study of a high-performance affordable housing community: The Woods (Figure 1). This BA effort is part of a larger-scale study of 30 homes funded from 2013–2016 by Tacoma Public Utilities (TPU) and the Bonneville Power Administration.

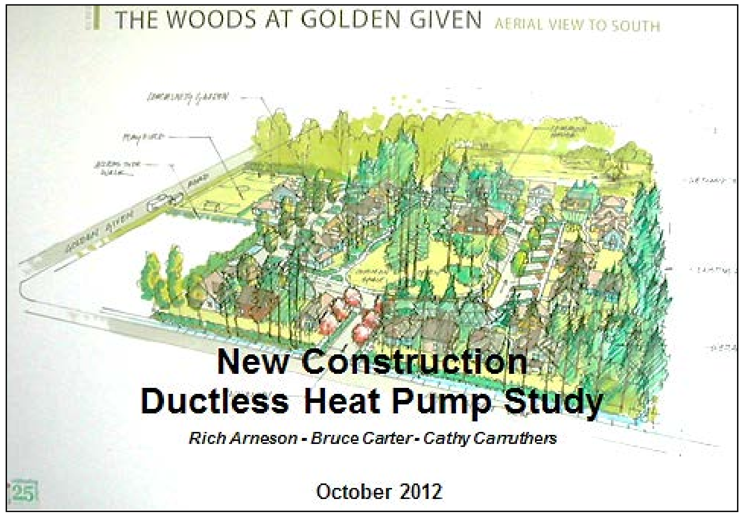


Figure 1. The Woods site plan

The Woods is a Habitat for Humanity (HFH) community of homes certified by ENERGY STAR® Homes Northwest (ESHNW); the community is in the marine climate of Tacoma/Pierce County, Washington. This research report builds on an earlier preliminary draft 2014 BA report and includes significant billing analysis and cost-effectiveness research from a collaborative and ongoing DHP research effort for TPU and the Bonneville Power Administration.

This final BA report focuses on the results of field testing, modeling, and monitoring of ductless mini-split heat pump hybrid heating systems in seven homes built and first occupied at various times between September 2013 and October 2014. The report also provides WSU documentation of high-performance home observations, lessons learned, and stakeholder recommendations for builders of affordable high-performance housing.

The research goal of the U.S. Department of Energy's BA research team Building America Partnership for Improved Residential Construction was to compare a ductless heat pump (DHP)-hybrid system (DHP in common area/electric resistance [ER] in bedrooms) to an all-electric zonal ER system in high-performance single-family affordable housing. This effort included assessing the costs and benefits of a DHP/ER hybrid system located in the main living area to offset the primary heating demand of zonal ER heaters in the bedroom zones and comparing these findings to data from of new affordable single-family housing in Washington State.

This report includes:

- Measured indoor and outdoor temperatures and relative humidity (RH) in the homes.
- Field testing results of heating, ventilating, and air-conditioning equipment; ventilation system airflows; building envelope tightness; lighting, appliance, and other input data required for preliminary Building Energy Optimization (BEopt™) modeling; and ENERGY STAR field verification.

- BEopt modeling results compared to measured energy use.
- A comparison of the space heat energy consumption of a DHP/ER hybrid heating system and a traditional zonal ER heating system installed in the same home. This comparison is made by implementing a series of weekly "flip-flop tests" (referred to here as "switchback" tests per TPU) to compare space heating, temperature, and RH in zonal ER heating mode with a DHP/ER mode as discussed in the Building America Test Plan (Lubliner 2010a).
- Cost data from HFH and other sources related to building efficiency measures focusing on the DHP/ER hybrid heating system.
- An evaluation of the thermal performance and cost benefit of DHP/ER hybrid heating systems in these high-performance homes employing life cycle cost analysis for energy code policy and monthly cash flow analysis of HFH homeowners.
- Post-monitoring occupant survey results.

The report also provides the following stakeholder findings and recommendations:

- DHP single-head systems at The Woods are cost-effective to new homebuyers of these high-performance all-electric homes.
- Stakeholder education is needed on design, inspection, and commissioning; documentation is needed for heat recovery ventilation (HRV) and from ENERGY STAR builders, verifiers, and inspectors to help ensure that the houses meet the goal of "build tight, ventilate right."
- A code gap in inspection and enforcement was identified that should be addressed by:
    - Improving the fire marshal's approach to sprinkler attic piping freeze protection;
    - Improving the maintenance of ceiling insulation continuity; and
    - Educating the local building inspector on attic insulation inspection concerns that allow for maximizing design improvements and performance of HRV attic ducting while ensuring ceiling insulation continuity (with respect to the location of HRV) in compliance with the Washington State Energy Code.

1 Introduction

This research effort included cost data collection, Building Energy Optimization (BEopt™) energy modeling, and in-situ monitoring of energy, temperature, and relative humidity (RH). The goals were to help determine the costs and benefits of adding a ductless heat pump (DHP) to the main living zone of new affordable single-family housing in the Pacific Northwest (PNW) marine climate; this high-performance housing is all electric.

Figure 2. Framing at The Woods

The U.S. Department of Energy's Building America (BA) research team Bulding America Partnership for Improved Residential Building conducted this research to help support BA goals to overcome barriers to installing DHP heating, ventilating, and air-conditioning (HVAC) systems in high-performance homes. Habitat for Humanity (HFH) may have difficulty justifying the higher installation costs of DHP compared to less expensive zonal electric resistance (ER) heating systems, given the relatively small space-heating energy costs and low utility rates for these very efficient homes.

However, DHPs may be a lower-cost solution in marine climates where the alternative is larger and centrally ducted propane (gas) furnace systems. DHP systems also include builder-installed air conditioning (AC), which is desirable as demonstrated by the growing AC market in the PNW marine climate. Unlike DHPs, centrally ducted HVAC systems that are not oversized are often difficult to find—even though they are required by mandatory energy codes and some voluntary energy programs. These programs include Challenge Home and ENERGY STAR Version 3, which delineate the industry-accepted practices as those defined in the Air Conditioning Contractors of America Manual S or other accepted HVAC sizing procedures.

Many centrally ducted gas and electric furnaces and air-source heat pumps are limited to minimum sizes, which leads to oversizing with respect to heating and/or cooling design loads. Oversizing occurs because smaller systems tend to be less available in the current HVAC marketplace (ASHRAE 2012). Smaller and centrally ducted HVAC systems may be more expensive per British thermal unit per hour (Btu/h) than the more available larger systems because of a lack of market pricing competition and economies of scale. This cost issue is especially important for HFH and other affordable housing stakeholders; they tend to build small homes with limited HVAC budgets and need to build with lower-cost ER heaters.

Unlike DHP/ER hybrid systems, single-speed HVAC systems that are oversized and centrally ducted often:

- Require ductwork that complicates placing the system in conditioned space;
- Have higher installation first costs associated with the box and ductwork;

- Have more design challenges for integrating whole-house ventilation;
- Have reduced zone temperature control;
- Reduce energy efficiency associated with equipment cycling; and
- Have more reliability issues related to maintenance, service, and useful life.

1.1 Research Questions

The primary BA research questions are listed below.

Q1 – What are the average annual electricity and bill savings of a hybrid DHP/ER hybrid heating system compared to the alternative all-electric resistance system in this study of HFH homeowners in a Pacific Northwest climate?

Q2 – What are the estimated total and incremental installed costs of hybrid DHP/ER hybrid zonal heating systems in new-construction single-family homes?

Q3 – What is the average expected life cycle and consumer monthly cash flow impact of a DHP/ER hybrid heating system compared to an all-ER heating system?

Q4 – How does the measured energy use and DHP savings compare with the BEopt model when field information about the home and occupants is known?

Q5 – Are participants at least as comfortable with DHP systems as with zonal electric systems, and what occupant behavior parameters may impact energy savings or thermal comfort, or both?

Q6 – What air-conditioning impact is associated with the DHP?

Q7 – What were the measured hourly indoor temperature and RH conditions in each switchback mode?

Q8 – What are the lessons learned during the design, construction, and verification commissioning phases of the project?

2 Background

Tacoma/Pierce County HFH is building 30 owner-occupied, single-family homes in the TPU service area during the spring of 2013 through 2017. The community is called "The Woods at Golden Given" and includes cottage-style dwellings of multiple designs ranging from 950 to 2,500 ft^2. These homes are all-electric with zonal heating in bedrooms as well as zonal heat and a DHP in the main living area. TPU has reviewed its service area account records and matched them with County Assessor data. Of the approximately 22,000 zone-heated homes in its service territory, nearly 25% are in this size range, and 41% are between 1,100 and 1,800 ft^2. Most new zone-heated homes are small and are representative of the four prototypes analyzed here.

HFH homes exceed current standards required by the Washington State Energy Code. Although floor and attic insulation is consistent with code, the exterior walls exceed code: 2 × 6, R-21 construction with 1 in. of extruded polystyrene (XPS) foam sheathing. To comply with Northwest ENERGY STAR Technical Compliance Options, TO1 Homes are required to be tested to be tighter than 4 air changes per hour at 50 Pascals (ACH_{50}), with ducted HRV systems installed and commissioned rather than exhaust-only ventilation (Northwest ENERGY STAR® Homes 2011).

Using higher-efficiency DHPs and other BA high-performance home energy-efficiency measures in smaller, single-story affordable housing will decrease the energy use of homes to help meet this goal. Interviews with the State Building Code Council Technical Advisory Group members and staff from the Washington State Department of Commerce revealed support for the overall project. Those interviewed also said that such a study is necessary for Washington to adopt a mandatory efficient heating code such as this DHP/ER hybrid heating system.

PNW builders of affordable housing communities such as The Woods, where natural gas is unavailable, often use all-ER heating and no AC. New energy codes reduce space-heating energy use, so it is difficult to justify the high first cost of higher-efficiency HVAC systems such as DHPs or centrally ducted furnaces and water heaters that use high-cost propane.

Research conducted in the PNW suggests that retrofitting older ER zone-heated homes with a DHP single unit ("head") in the main living area may displace 3,000–5,000 kWh/year (Ecotope 2013, 2014). The research indicates that adding additional DHP heads in more zones of the home was not cost-effective, suggesting that DHP displacement is a function of the energy efficiency of the home and the behavior of the occupants; specifically, their reliance on the DHP for primary heating. Leaving bedroom doors open and improving the mixing of DHP zone air with other zones is important for maximizing DHP savings and providing a cost benefit to the homeowner.

2.1 Previous Ductless Heat Pump Performance

DHPs perform well over a wide range of temperatures and operate much better than their larger ducted heat pump "cousins." The National Renewable Energy Laboratory (NREL) and Ecotope conducted an independent lab study in 2012 of two typical DHP models: the Fujitisu 12RLS and the Mitsubishi FE12NA (Ecotope 2013).

The Fujitisu unit tested by NREL is an older version of the Fujitsu 12RLS installed for this study. In general, the study concluded that manufacturer performance specifications aligned with independent testing results. The performance results outlined in Section 5 support the assertion that DHPs are capable of supplying adequate heat to a home with much lower than Washington state design temperature requirements.

NREL conducted British thermal unit output performance testing over a wide range of outside temperatures and operating modes. Performance testing results of the Fujitisu unit at intermediate (manufacturer data) and maximum (NREL data) compressor speeds suggest this unit can supply more than 10,000 Btu/h at intermediate compressor speeds even at 0°F and was able to supply more than 12,000 Btu/h at maximum compressor speed. NREL also performed coefficient of performance testing over a wide range of outside temperatures and operating modes.

2.2 Residential Air Conditioning in Washington State

DHPs offer homeowners the additional benefit of cooling. Although this is typically perceived favorably by homeowners, it increases energy use in homes that would otherwise have all ER heating and no air-cooling system, which this study takes into account.

This study assumes that homes on the alternative all-ER heating systems would have had no AC; however, market assessments clearly indicate that many households do, in fact, have AC systems. The Residential Building Stock Assessment found that approximately 24% of all single-family homes surveyed had some form of cooling equipment in Washington state's cooling zone 1 (western Washington) and 72% in cooling zone 2 (eastern Washington).

TPU's most recent Residential and Appliance Saturation Survey in 2011 found that nearly 34% of single-family homes have some form of cooling system. Most of these were portable or window air conditioners.

2.3 Study House Size Is Representative of Housing Stock

Over the last 20 years in the TPU service territory, new-construction single-family, zone-heated homes averaged 1,462 ft^2. The average size of homes with other heating systems for the same period was 2,000 ft^2. The average home size in this study is 1,280 ft^2, just 180 ft^2 smaller than the average zone-heated home in the TPU service territory.

2.3.1 Geographic Location

Project sites are located in Pierce County in the western Washington area known as South Sound (Figure 3).

2.3.2 Occupant Characteristics

All homes are occupied as primary residences. The number of bedrooms in each home is dependent on the number of occupants. HFH's model design ensures that each child in the household has his or her own bedroom. In practice, children in some homes share bedrooms; the additional rooms are used as play rooms, offices, etc.

A participant survey was conducted. Occupants of the seven homes considered in this study consist of one or two parents and their children, and the total number of occupants ranged from three to six. Five of the seven households have children younger than 12 and three of the seven have adolescents aged 13 to 17.

Home occupancy varies somewhat during the daytime. Three households reported having regular times of the day when the homes were unoccupied during the week; four reported that their houses were virtually always occupied.

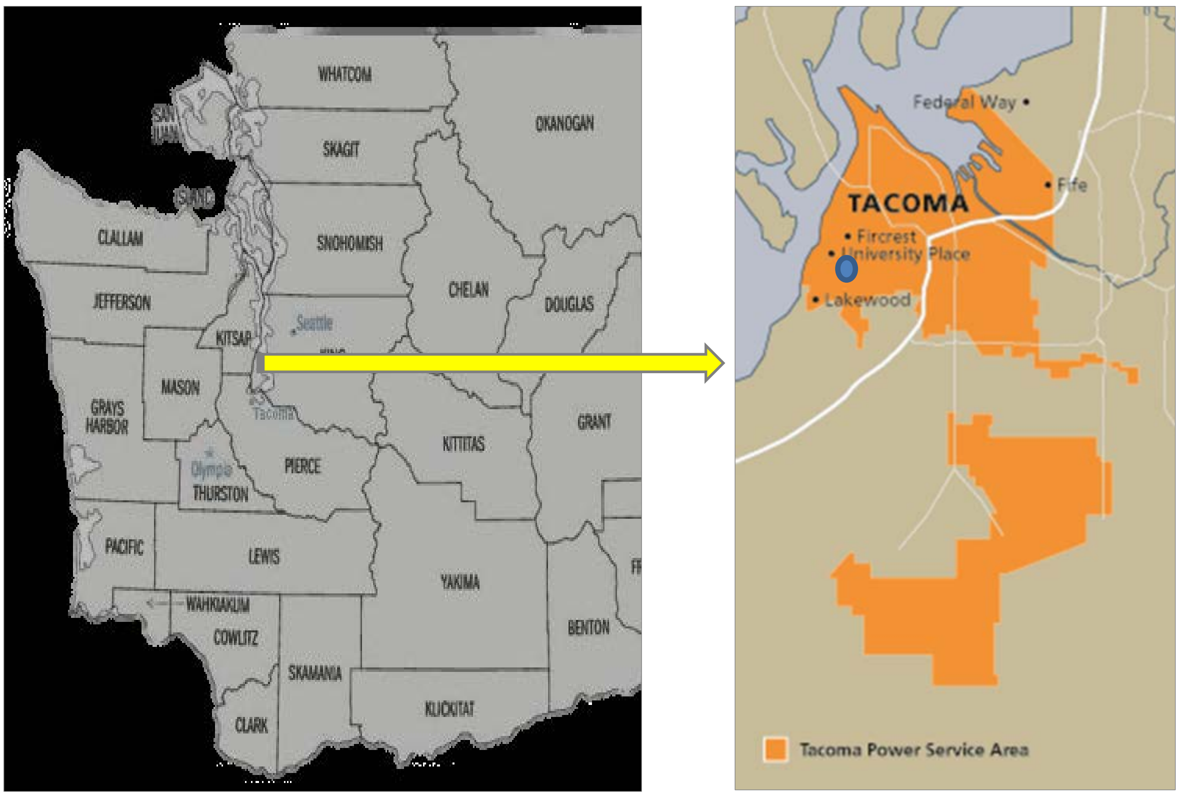


Figure 3. Washington state, the South Sound area, and the project site

3 Research Approach

The research approach is based on previous BA research performed by the WSU Energy Program that employs weekly "switchback" testing of DHP compared to a central electric furnace in a manufactured home (Lubliner 2010b, Section 2.2.6). This project used the switchback testing method to gather new DHP relative performance information.

The earlier research suggested that DHP performance was more than twice the coefficient of performance relative to the central furnace operation. Challenges were noted in maintaining bedroom temperatures during colder periods. Lessons learned in previous switchback testing of DHP and collaboration with utility billing analysis experts have helped to inform this project.

This research also looks at the nonenergy tradeoffs associated with occupant comfort by assessing occupant surveys and monitored data of temperature and RH zonal distribution during heating and cooling seasons.

3.1 Relevance to Building America's Goals

The U.S. Department of Energy's BA program strives to "reduce home energy use by 30% to 50% (compared to 2009 energy codes for new homes and pre-retrofit energy use for existing homes)." To this end, the WSU Energy Program proposes DHP/ER hybrid heating as a market-ready solution to improve HVAC efficiency and comfort in new single-family homes in the PNW marine climate that are affordable, all electric, high-performance, and site built. The results are scalable to thousands of affordable housing units built in the PNW marine climate and other U.S. heating climates where natural gas is not available and propane or fuel oil are more expensive than electricity. Adding AC to these homes also improves summertime occupant comfort and may displace aftermarket and less-efficient occupant-installed "window shaker" AC units.

3.2 Ductless Heat Pump Hybrid Heating Systems

For this study, all homes are heated with DHPs, ER baseboard heaters, and fan-assisted wall heaters. Each home has a single air handling unit (indoor head), 1-ton DHP with a heating seasonal performance factor (HSPF) of 12 and a seasonal energy efficiency ratio (SEER) of 25. The DHP's interior unit (head) is installed in the main living area of each home in addition to 2,500 watts of installed baseboard heater. These homes have the same DHP model installed. This equipment is pictured in Figure 4.

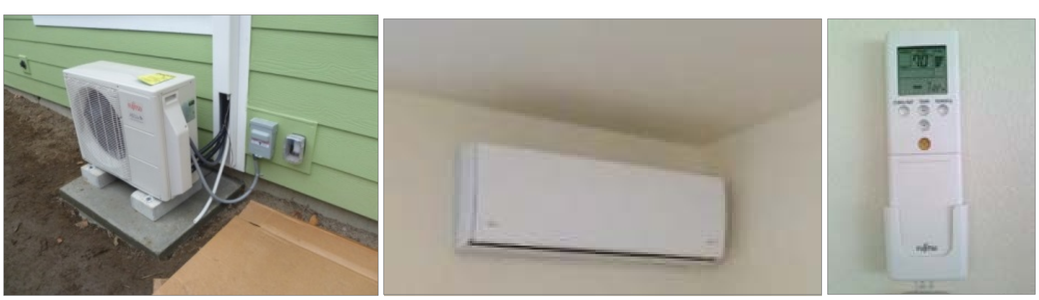


Figure 4. Outdoor and indoor DHP units and remote thermostat in living room

Each bedroom in these homes is directly heated with one 750-W fan-assisted ER wall heater located in the exterior wall below a window. All zones are controlled by independent manual thermostats. This equipment is picture in Figure 5 along with a data logger adjacent to the thermostat.

Figure 5. ER, fan, and baseboard types and hard-wired thermostat in living room with temperature/RH data logger

Table 1 shows the combined heating wattage of DHP/ER hybrid at outdoor air temperatures (OATs) of 47°F and 17°F. The combined heating wattage of DHP/ER hybrid at 47°F and 17°F for the five-bedroom El Jeffe (Pine) is 8,438 W to 6,592 W, respectively. The winter design condition for this area is around 17°F. The ER design load capacity is 342 W less than the DHP/ER hybrid home at the 17°F design heat load; however, the DHP/ER hybrid at 47°F has a 2,188-W higher output range.

Table 1. Installed Capacity (Watts) by House Type,[1] Heating System Configuration, and OAT

	Jeffe	Jameson	Cottage	Lakewood	Double-Front
ER Output with Living Room Baseboard	**6,250**	4,000	4,750	4,750	5,500
ER Bedroom Output without Living Room Baseboard	3,750	3,750	3,750	3,750	3,750
DHP Output Only @ 47°F	4,688	4,688	4,688	4,688	4,688
DHP Output Only @ 17°F	2,842	2,842	2,842	2,842	2,842
DHP/ER Hybrid Output @ 47°F	**8,438**	6,188	6,938	6,938	7,688
DHP/ER Hybrid Output @ 17°F	**6,592**	4,342	5,092	5,092	5,842

3.3 Cost-Effectiveness

This study evaluates strategies that further improve DHP cost-effectiveness, including improving energy savings from DHP/ER hybrid systems and reducing first costs of installation. The WSU Energy Program field team collected DHP construction costs and used monitoring data and incremental cost data to assess cost-effectiveness. This included:

[1] House types are shown on Page 14.

- Performing life cycle cost analysis (LCCA) and consumer monthly cash flow analysis of energy savings based on switchback testing to inform the space-heating assumptions of DHP versus ER heat.
- Collecting cost data (labor, time, and materials) for each aspect of the DHP installation and comparing them to RSMeans estimates for typical market rate construction data.
- Surveying occupants at the project conclusion to gather feedback about comfort and other considerations during the DHP and/or ER heat switchback tests.

Cost-effectiveness analysis employed two approaches: (1) a monthly cash flow consumer analysis and LCCA for energy code policy, and (2) post-monitoring occupant survey results.

3.4 Building Energy Optimization Modeling

BEopt Version 2.02 was used to estimate the typical space-heating and total annual energy use for seven homes. The analysis was conducted for an all-ER heat case and an all-DHP case (which displaces all-ER rather than hybridizes with ER as in the actual experiment). Thermostat heating and cooling set points are based on field measurements and occupant surveys for each home. The envelope leakage is based on blower door tests conducted by the WSU Energy Program field team or ENERGY STAR verifier, or both. All house characteristic information used in the BEopt analysis is included in Appendix A.

BEopt modeling attempted to model the home "as-built" to allow for a more finely tuned comparison of BEopt to actual performance, instead of using only BEopt default assumptions, based on plans. Three homes used the Cottage plan and two used the double-front plan.

Because BEopt is a single-zone model, it is limited in its ability to model hybrid multizone heating systems. BEopt modeling of energy savings evaluated displacement of the ER space heating kilowatt-hours. The BEopt model results were compared to the home's actual energy use to better understand the overall energy use and savings from DHP/ER hybrid heating systems versus all-DHP or all-ER systems.

3.5 Error Checking and Energy Use Data Quality Control

The data logger vendor uploads enabled electronic data delivery from the data warehouse to TPU computers. Data were reviewed after field installations and scaling of the data channels was verified and corrected if necessary. Once downloaded, data were subjected to range and sum checks. These checks ensured that data used in the analysis were logically accurate (total household energy use was never lower than use from a single channel). Significant time was invested to ensure switching schedules were accurate by verifying site consumption and temperature data.

3.6 Heating Analysis Methodology

Researchers conducted the following HVAC switchback experiments:

- Placed time clocks and data loggers on the electrical circuits for the ER zonal heat and the DHP in the common living area.

- The time clock cycled weekly between the DHP and the zonal heat in the common area. Occupants were instructed to operate each system to maintain comfort using the thermostats and controls for the DHP and zonal heat.
- ER heat in the bedrooms and other rooms was controlled by the occupants and was unaffected by the time clock.
- Time clocks were locked so occupants could not alter the metering cycles.

Data loggers monitored the zonal electric heat circuits for the rest of the home to capture electricity consumption in those areas. Each home was assigned a DHP start day: Monday, Tuesday, Wednesday, etc. The cycling must shift each day so homes change status each day; this allows each home to perform as both an experimental case and as a control for itself (in a crossover comparison) and others (in a parallel comparison). Data analysis uses both cross-sectional and parallel analysis.

The analysis of electricity use data during the heating season was conducted for seven houses (Pine, Larch, Fir, Hemlock, Alder, Oak, and Cedar). Five other occupied houses were not included in the analysis due to limited data; they were occupied late in the study or presented other data problems (e.g., one homeowner used a portable electric heater in the common area; in another house an ER heater was incorrectly wired so it was permanently on).

The analysis period varies for each house depending on when it was first occupied. Pine was first occupied at the end of September 2013 and Alder was occupied in October 2014. The analysis focused on the heating season. During the summer, the switchback experiment was stopped so occupants could use the DHP for cooling. This occurred from July 11 to Sept. 14, 2014, after which the switchback experiment between heating modes was resumed.

This summer period was excluded from the heating analysis. The DHP was intended to be in heating mode the rest of the time. An occupant may have switched the DHP to cooling mode during the heating period, but any cooling use was likely minimal and should not have affected the results. Occasionally, western Washington experiences warm days in May or June, but the weather typically is relatively cool during this period. The average measured outdoor temperature at The Woods in June 2014 was 59°F, with a minimum of 45°F and a maximum of 76°F. The need for cooling in these well-insulated homes at The Woods during this period should have been minimal.

Data were compiled for each weekly switchback period in DHP and ER mode and compared to obtain estimates of actual energy use and savings. A multivariable linear regression analysis was used to correct for differences in the analysis periods, houses, and weather between modes to produce an overall savings estimate for the group of houses. Variable degree-day linear regressions were conducted for each house to normalize the annual energy-savings estimates to typical weather conditions. The results of the heating energy analysis were compared to the output from the BEopt energy modeling. Factors influencing energy savings from the DHP such as indoor temperature, occupant behavior, and cooling energy use during the summer were considered.

3.7 Field Monitoring

For this study, WSU Energy Program staff placed the data logger systems. Bates Technical College student electricians (overseen by their instructor) installed wiring, current transducers (CTs), time clocks, and contactors. WSU developed a field installation guide in the early stages of field installation. Site technicians were required to fill out a detailed site protocol, including types of sensors and individual sensor serial numbers, because these are the primary identifiers of sensors after data return from the data logging vendor.

Currently, 12 homes are occupied and monitored with data logger systems. This report analyzes data from seven homes. The remaining five homes have wiring or occupant behavior challenges that have rendered the data unusable at this time.

End-use metering using a HOBO U30 data logger included hourly measurements of whole-house energy use, ER and DHP energy use in the common living area, ER energy use in other conditioned rooms in the home, domestic water heater energy use, and the vapor line temperature at the DHP. Temperature and RH were also logged for the common living area and two bedrooms using stand-alone HOBO data loggers. The HOBO monitoring equipment specifications are provided in Appendix H.

The data logger vendor's cellular modem enabled electronic data delivery from the data warehouse to TPU computers. A documented process was used to configure and manage data logging equipment. HOBO U30 data loggers measured the energy use of key electrical circuits to quantify space-heating energy use within study homes. It also quantified cooling energy use (Figure 6).

A 100-amp CT was installed by electricians at each 120-volt leg of the main service panel to collect data on all end uses of the home (Figure 7).

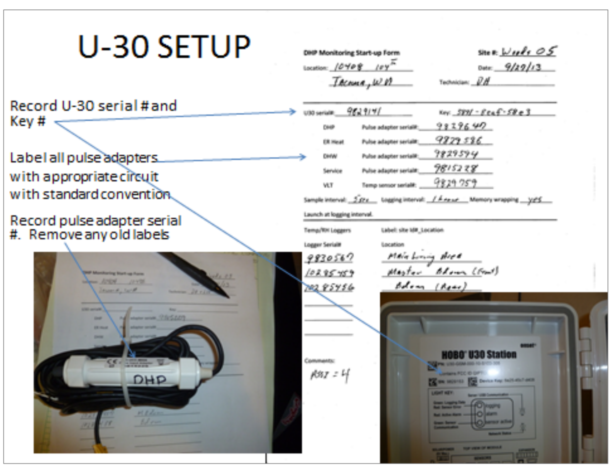


Figure 6. Data logger commissioning

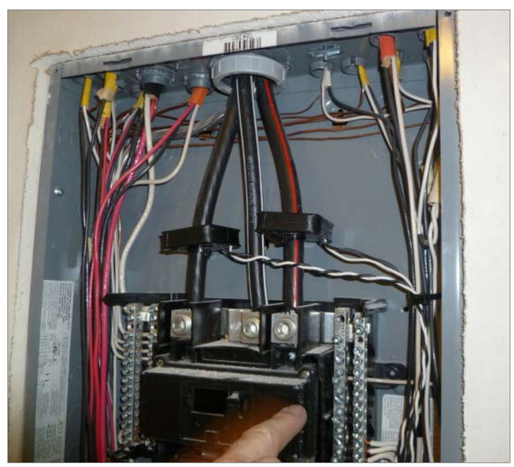


Figure 7. Service panel CTs to measure all-electric load

A 50-amp CT was installed by electricians at each 120-volt leg serving the common living area. A contactor for the DHP and the common area ER zone was switched each week with an electronic time clock. All other ER zonal heating was controlled by individual thermostats and not with the time clock system, and CTs were installed to separately measure energy use of these heating circuits. One CT was installed by the electrician on one 120-volt leg of the domestic water heater (Figure 8). This CT was scaled at twice the value to account for energy use of the two 120-volt legs that serve the DWH. At each home, a vapor line thermistor was taped directly onto the small refrigerant line, wrapped with insulation, and zip tied in place (Figure 9). The vapor line thermistor data provide information about the DHP operation.

At each home, a temperature/RH data logger was placed in the common living area and in two of the bedrooms and logged at hourly intervals. For each room, the data logger was placed adjacent to the thermostats that control the ER zonal heating (Figure 10).

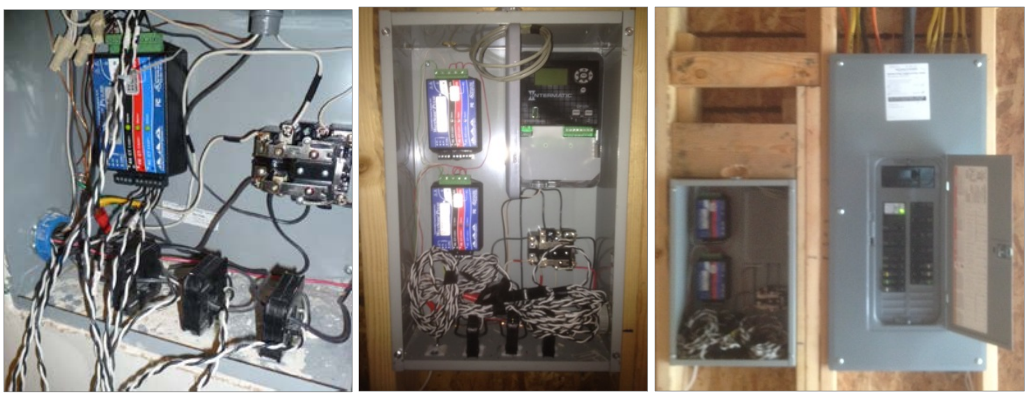


Figure 8. Panel containing time clock-contactors-CTs for switchback and monitoring

Figure 9. Vapor line thermistor

Figure 10. Indoor temperature/ RH data logger at zonal thermostat

3.8 Data Collection and Assembly—Energy Use Data Collection Time Frame

The researchers looked at total kWh used by two channels responsible for heating: a 240-volt circuit for living room heat (switched between DHP and ER) and a 240-volt circuit for ER in other parts of the home.

Data collection for each house was dependent on HFH's dwelling construction and occupancy schedule. The length of time in this study ranged from 2 months to 15 months. Individual home details are provided in Appendix D.

The TPU aggregate home analyses used data from move-in date through Jan. 21, 2015. The median number of data-days per site for the entire sample was 278 days; the longest (Pine) was 377 days and the shortest (Alder) was 64 days. Data through Jan. 20, 2015 were downloaded directly from HOBOLink and compiled into a master file for analysis.

4 Field Visit House Characterization

For this research project, WSU Energy Program staff performed detailed audits of the first eight homes built in The Woods development. The purpose of these audits was to provide information for BEopt and to help inform the analysis of monitoring data. Equally important, the audit findings and associated technical assistance helped provide feedback to HFH and stakeholders to improve and maximize the benefits of high-performance homes in this community and future projects. Most of this technical assistance focus was associated with the "build tight and ventilate right" philosophy of high-performance homes.

4.1 General Specification Summary

The test homes range in size from 895 ft^2 to 1,391 ft^2. Six were two-story homes with three or more bedrooms, and the smallest home had one story with two bedrooms. All homes in the development were built to identical specifications with limited modifications. All homes in the development are required to have fire sprinkler systems due to small-lot densities.

Roof structures are all variations of ventilated attic systems with raised heels. Attics are all insulated with blown loose-fill fiberglass to a minimum of R-49 in the field and a minimum of R-21 at exterior wall edges. The area weighted average U-factor of all glazing is 0.29.

The lots in this development are fairly small, and the houses were built within minimum required setbacks. In some cases, the density of each lot compromises potential solar access. Test home characteristics are described in Figure 11, Figure 12, Table 2, and Table 3.

The homes are all built over a slab-on-grade. These slabs are fully insulated with R-15 XPS with an R-15 separation between the slab edge and the stem wall.

Wall construction employs advanced framing methods with double top plates and headers insulated to R-10. Wall cavity insulation is R-21 fiberglass batts with a single continuous layer of R-5 XPS providing a thermal break exterior to the wall sheathing. The one large exception is the window rough opening, where HFH furred out the window in wood framing because of concerns about siding and window flange installation.

Furred-out window flange and trim nailer to accommodate 1-in. XPS foam sheathing and window trim.

R-10 insulated headers and raised heel trusses

Raised heel truss showing accommodation for installation of a minimum of R-21 insulation plus ventilation baffle.

Advanced framing 24 in. on center, insulated headers, and air-sealing measure.

Figure 11. Test home building characteristics

The “Cottage” is a 1,267-ft^2 two-story home with three bedrooms and two bathrooms. It is flanked by two-story homes to the east and west, and its street frontage is to the south.

The “Jameson” is a one-story, 895-ft^2, two-bedroom, one-bathroom home with minimal solar exposure. This home sits on an inside corner with two-story homes to its south and east.

The four-bedroom “Double-Front” is a two-story, two-bathroom, 1,312-ft^2 house with street frontage to the east, a sparsely wooded lot to the west, and a two-story home to the south.

The three-bedroom “Lakewood” is a single story, 1-½ bath, and 1,333-ft^2 house with street frontage to the east.

Figure 12. Test home characteristics

Table 2. Test Home Characteristics

Measure	Description for BEopt Inputs for Modeling
Slab Insulation	R-15 (3-in. XPS)
Wall Insulation	R-21 + R-5 XPS c.i. (24 in. o.c.)
Windows	Area weighted U-factor = 0.29
Ceiling	R~49 with minimum of R-21 at exterior wall edges
Space Heating	1-ton single-head DHP and (2-1,250-W) 2,500-W electric baseboard in main living space 750 W of fan-assisted ER wall heaters used in each bedroom with individual zone controlled thermostats
	250-W heat lamps in bathrooms on switch
Water Heating	0.91 energy factor 50-gal electric storage type
Lighting	100% high-efficacy lamps
Dishwasher	ENERGY STAR—Whirlpool DU810SWPQ4
Refrigerator	ENERGY STAR—Whirlpool W8TXEWFYQ01
Clothes Washer	ENERGY STAR—Whirlpool WFW70HEBW0
Ventilation	Fantech FLEX100H sensible recovery efficiency at 0.3 in. = 64%

The BEopt energy modeling used as-built conditions as much as possible. Minor variations between as-built and BEopt include:

- BEopt used McChord Air Force Base Typical Meteorological Year 3 (TMY3) data.
- BEopt used reported occupancy and thermostat setting based on HOBO temperature data.
- BEopt used R-15 fully insulated slab.
- HRV efficiency = 70% used in BEopt versus 63% as-built "HVI rated."
- HRV flow rates were measured at commissioning on low speed.
- HSPF = 11.6 in BEopt versus HSPF = 12 as-built "ARI rated."

Table 3. Test Home Descriptions

Code	Plan Type	Stories	BR	Bath	Area (ft^2)	Occupants	Solar Orientation	ER Heating Output (W)
Pine	El Jeffe	2	5	2	1,391	6	South	6,250
Larch	Cottage	2	3	2	1,267	4	South	4,750
Fir	Double-Front	2	4	2	1,316	4	East	5,500
Hemlock	Cottage	2	3	2	1,267	3	East	4,750
Alder	Double-Front	2	4	2	1,316	4	East	5,500
Oak	Lakewood	1	3	1.5	1,133	3	East	4,750
Cedar	Cottage	2	3	2	1,267	5	East	4,750
Maple	Jamison	1	2	1	895	2	South	4,000

Most water fixtures were rated as low flow, but actual measured flow rate did vary:

- Shower head flow rates varied from 1.5 to 2.5 gallons per minute (GPM).
- The kitchen faucets tested consistently at 1.75 GPM.
- The utility sinks tested to roughly 4 GPM.
- Aerators are present on all bathroom sinks but flow rates were not tested.

Domestic hot water is provided by 50-gal electric storage-type water heaters with an energy factor of 0.91. The ENERGY STAR Homes Northwest (ESHNW) Builder Option Package 1 standard requires a minimum energy factor for electric storage-type water heaters of 0.93. The Tacoma/Pierce County Affiliate of HFH was allowed a tradeoff with R-5 exterior continuous wall insulation for the reduced water heater efficiency. All water heaters were located in an insulated but unconditioned mechanical room attached to the home and accessed from the exterior. Each home has a Fantech HRV that provides whole-house ventilation. The HRV model used is identical in each home, but duct design/layout and location of the HRV vary. These HRVs are designed to run continuously at low-speed flow rates targeting ASHRAE 62.2 minimum airflow requirements. Local exhaust fans were installed in all bathrooms, utility rooms, and kitchens per code.

Appliances for the homes consist of ENERGY STAR refrigerators, clothes washers, and dishwashers supplied by HFH. All clothes dryers and ranges are electric. The four homes tested had 25–40 lamps in hard-wired lighting fixtures. All lamps fitted in hard-wired fixtures are high efficiency except heat lamps in each bathroom (250 W) and range hood task lighting.

5 Results and Discussion

5.1 Field Testing Results

The homes tested at The Woods were the first homes built in the development. However, the Tacoma/Pierce County affiliate of HFH has been building homes with exterior-applied continuous insulation and advanced air-sealing and framing techniques for a few years. Given this, the WSU Energy Program researchers expected little variation in performance testing results in the four homes that were audited. However, much of the construction labor was provided by volunteers, so some inconsistency in installation technique and quality was expected, particularly in relation to the installation of the air barrier.

5.1.1 House Tightness

Maximum air-leakage rates in the building envelope were tested and documented for each home (Appendix G). The ESHNW program and the Washington State Energy Code both require this test to be performed before the home is occupied. The ESHNW maximum allowed envelope leakage rate is 4 ACH_{50}, and the state code maximum allowable leakage rate is 0.00030 specific leakage area. Test results are summarized individually in Table 4 and range from 3.15 to 4.32 ACH_{50}.

Table 4. House Tightness Information

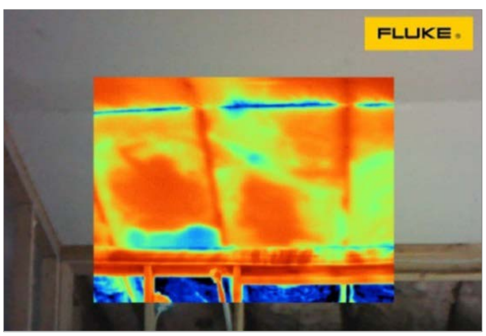
Code	Plan Type	Bath	Area (ft^2)	CFM 50 Pa	ACH_{50}
Pine	El Jeffe	2	1,391	648	3.29
Larch	Cottage	2	1,267	753	4.32
Fir	Double -Front	2	1,316	715	4.16
Hemlock	Cottage	2	1,267	693	4
Alder	Double-Front	2	1,316	612	3.4
Oak	Lakewood	1.5	1,133	542	3.5
Cedar	Cottage	2	1,267	658	3.8
None	Jamison	1	895	376	3.15

All homes were subject to multiple multipoint blower door tests under varying conditions. Several tests were performed to understand and diagnose specific areas of leakage. The Larch and Cedar homes had significantly higher air-leakage test results due to more attic knee wall area and a more complicated roof line than the other homes (according to HFH staff) and have had air sealing difficulties with this design in the past. Infrared (IR) imaging showed areas of significant air leakage at wall-to-roof truss intersections, rim joists, bottom plates, and ceiling- and floor-to-wall intersections where the front porch roof trusses abutted the thermal boundary. Unfortunately, these areas are practically inaccessible for postconstruction air-sealing efforts. However, with the aid of IR imaging, HFH and WSU Energy Program staff applied some postconstruction air-sealing measures. The air-leakage rate for Larch was reduced from 4.65 to 4.32 ACH_{50} as a result of these efforts. Most of the resulting air-leakage reduction was accomplished by applying a better air barrier at the bathroom fan housings and attic access hatches and at the mechanical closet containing several plumbing penetrations for the fire sprinkler system.

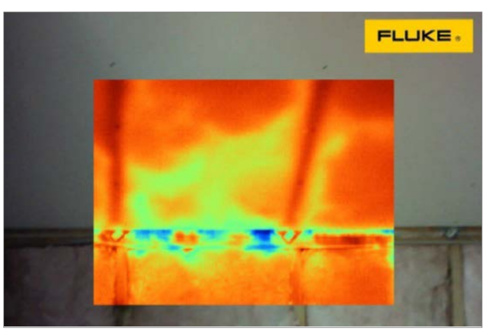
The air-sealing quality assurance checklists were not used during HFH's quality control process, and the nuances of a complicated roof plan likely contributed to the high air-leakage test result for the Larch home. Air-leakage test results have decreased from the first to the second home built of this type; slightly for the Cottage (4 to 3.8 ACH_{50}) and more for the Double-Front (4.16 to 3.4 ACH_{50}) in these identical plan homes.

The ESHNW standard requires that a contractor complete the thermal bypass checklist. This checklist is intended to aid in quality control over a home's air barrier. This process must be verified before the home is certified. In Larch, this checklist was verified to have been completed. However, quality control can be much more difficult and require much more effort for organizations that depend largely on volunteer and unskilled labor, and access to IR imaging for quality assurance feedback is not typically available to HFH.

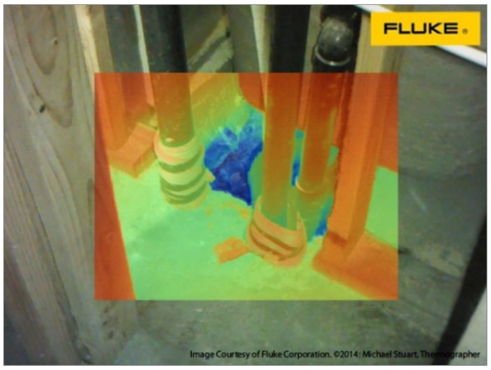
Early in the project, WSU Energy Program staff scheduled an informal air-sealing and insulation installation training at The Woods for the HFH construction supervisors and the ESHNW verifiers on this project. Michael Stuart and Tony Shockey of Fluke joined the group to share their expertise in thermal imaging as a tool to identify areas of thermal bypass. The group evaluated a home before wall insulation was installed but after all intentional thermal envelope penetrations were sealed to help identify leakage paths. Thermal imaging and unaided visual and physical inspection were performed under normal heating season conditions and with the home under –50 Pa of depressurization. The images in Figure 13 illustrate the significant findings of this exercise.



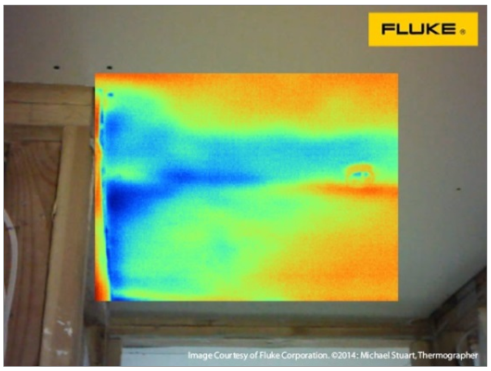
Gaps, voids, and compression of insulation
Void or gap in insulation at rake and flat ceiling intersection
Compression and void in insulation at rake and wall intersection



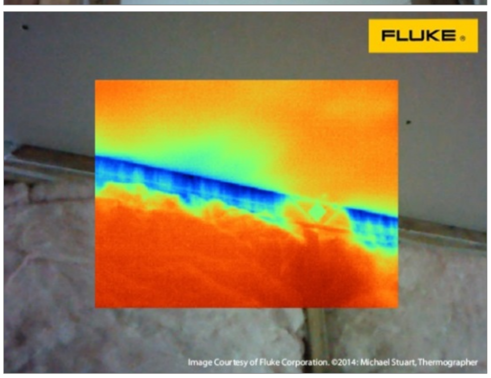
Air leakage at the roof rake to knee wall intersection
On this project, HFH used a strip of compressible foam behind the wall sheetrock to prevent this leakage from entering the vented attic area.



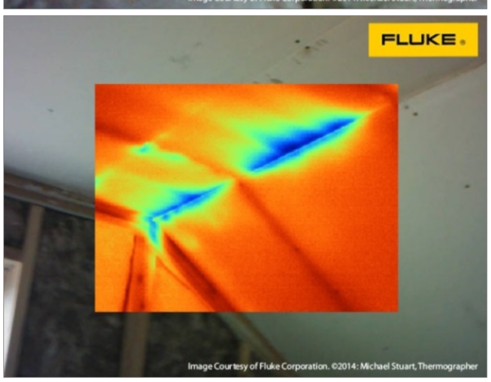
Unfilled cut-out in slab to allow for plumbing



Incomplete fill of ceiling insulation



Air leakage at the ceiling-to-top-plate intersection
On this project, HFH used a strip of compressible foam behind the wall sheetrock to prevent this leakage from entering the vented attic area.



Air leakage void, gaps, and compression of insulation

Void and compression of insulation in a wall cavity wiring intersection

Figure 13. Areas of thermal bypass

5.1.2 Sealed versus Unsealed Sprinklers

In addition to understanding the factors that impact air-leakage pathways in these homes, WSU Energy Program staff was interested in determining the contribution of each home's fire sprinkler system on the overall leakage rate of the home. This affiliate of HFH installed a site-constructed rigid foam box over the sprinkler head hardware in the attic as an air-sealing measure. This box was sealed to the sheet rock before the insulation was installed. The two homes that were evaluated, Larch and Maple, had sprinkler heads that were sealed to the interior with tape before a multipoint blower test using TecTite software was run.

- At Larch, sealing the sprinkler heads with tape reduced less than 1% of the total CFM_{50} of the home from 811 to 804.
- At Maple, sealing the sprinkler heads with tape reduced 7% of the total CFM_{50} by 25 CFM_{50}, from a normal operation of 376 CFM_{50} to 351 CFM_{50}.

From this small sample, one could conclude that the variation in measured flow rate was as likely to be from exterior pressure fluctuations from wind and other test conditions as from leakage. However, lack of attention to details and quality control issues when installing sealed boxes above the sprinkler heads was as likely to be a contributing factor. The WSU Energy Program team is working with the local fire marshal and sprinkler manufacturers to clarify installation procedures.

In addition, the fire marshal required "tenting" of batt insulation over the sprinkler piping in the attic, even after the engineer showed that the insulation required in the energy code would provide sufficient freeze protection in the attic. The fire marshal apparently requires more education about Washington State Energy Code requirements; this issue needs to be addressed through further stakeholder discussion.

5.1.3 Heat Recovery Ventilation and Intermittent "Spot" Ventilation

These homes were all designed to meet ASHRAE Standard 62.2-2009 ventilation requirements for local exhaust and whole-building ventilation. The local exhaust ventilation systems in the bathrooms and utility rooms were all independent exhaust fans that were manually controlled by twist or push-button timers. Kitchen exhaust systems were manually controlled two-speed range hoods or two-speed range hood/microwave combination fans. The whole-building ventilation systems have two-speed capacity and were sized to run continuously at low or high speed, depending on each home's minimum ventilation rate calculation.

In the initial design, all but the kitchen local exhaust requirements were met with the HRV. However, interpretation of the ventilation code requirements by the local building department did not allow this strategy. Two code issues that should be carefully examined occurred when local code officials did not allow:

- The HRV to meet local exhaust requirements
- HRV ducts in the ceiling insulation to prevent voids.

Additional stakeholder dialogue is needed to clarify that HRV ductwork can be buried in the attic insulation and that the local jurisdiction should not require that the ducting be placed above the ceiling insulation. This increases the HRV duct run surface and run lengths and increases the overall HRV duct heat loss. In fact, the official requirement to prevent voids in the ceiling insulation is causing greater heat loss from the HRV ducting than any small voids covered by ceiling insulation.

All bath, utility room, and kitchen range fan flow rates were measured by WSU Energy Program staff during the audits of the first four homes. This included the whole-building ventilation system and all local exhaust fans. For most cases, flow rates were measured at the interior diffuser for the fan, but in some cases measuring the flow rate from the fan's exterior terminus was most practical. Some of these measurements were taken from both the interior and exterior ends of the system.

The bath fan at Maple measured 39 CFM from the interior and 43 CFM from the exterior. This fan has a rating of 110 CFM at 0.1 in. water gauge and vented straight vertically through roughly 4 ft of ductwork. The terminus screen was clean of debris, and the terminus barometric damper was functioning properly. The field team suspected that the ductwork for this fan may be kinked somewhere below the level of the blown attic insulation. It was also speculated that the barometric damper on the fan housing itself may be partially blocked by fasteners used to secure the ductwork to the fan housing.

In general, local exhaust fan flow rates were taken from the interior of the homes with either the Alnor Jr. Balometer or The Energy Conservatory Flow Box. However, due to difficulties fitting either of these flow hoods properly to the range hoods, the field team had better success taking these fans measurements at the roof terminus. Nearly all flow rates measured met ASHRAE 62.2 and the ventilation and indoor air quality intermittent flow rate standards for local exhaust. Table 5 is a summary of all exhaust fan flow rates measured in the four homes that were audited.

Table 5. Local Exhaust Fan Measurements (CFM)

Location	Fan Type	Pine		Larch		Maple		Fir[a]	
1st Floor Bath	Single speed	82		68		39		44	
2nd Floor Bath	Single speed	60		65		N/A		66	
Utility Room	Single speed	48		55		54		76	
Range Hood	Two speed	105	65	104	22	160	93	14	14

[a] Range hood in Fir was repaired to fix the stuck damper.

The first-floor bath fan at Fir and the utility room fan at Pine measured slightly lower than ASHRAE 62.2 minimum flow standard for these spaces. These fans were both rated to provide 50 CFM of flow at 0.1-in. water gauge. This does not allow for much tolerance of less-than-perfect duct design and installation. This realization indicates that the fan rated to 110 CFM at 0.1-in. water gauge at Maple must have considerable issues with the ductwork. This issue should be examined in light of the equipment's durability and its failure to meet the ESHNW and ASHRAE Standard 62.2 ventilation requirements.

Three of the range hoods that were measured met minimum flow rate requirements of ASHRAE Standard 62.2 while running at high speed. The range hood at Fir was measured from the roof terminus with the Alnor Jr. Balometer and measured the same flow rate of 14 CFM at both speeds. This was the same microwave range hood used at Maple. In both homes, an aftermarket barometric damper was installed at the fan side of the duct system. This damper at Fin made a loud noise when the fan was activated, leading WSU Energy Program staff to believe that it was installed backward and was closing when the fan was activated. HFH staff was alerted to and resolved this issue by reversing the direction of the interior damper. Flow measurement equipment specifications are provided in Appendix H.

All four homes addressed whole-house ventilation requirements with Fantech two-speed HRVs (Figure 14). These HRV units were located either in a conditioned utility room or in an unconditioned, insulated mechanical/storage room shared by the home's water heater. Flexible insulated (R-4) ductwork was used to supply outside air to the house and exhaust interior air to the exterior. Ductwork was hung from the top cord of the roof trusses in the vented attic and run between floors in the two-story homes. Initially, the design was to run the ducts in the attic across the top of the bottom cord of the roof truss in the attic. These ducts would then be buried in loose-fill insulation. As discussed earlier, the local code enforcement's interpretation of energy code requirements prevented this design from being implemented. WSU Energy Program staff members are undertaking efforts to educate HFH and the building department staff about interpreting the Washington State Energy Code requirements. Ideally, the jurisdiction will amend its interpretation to allow HFH and all other builders to bury these ducts in the required attic insulation and provide exhaust via the HRV on all future homes.

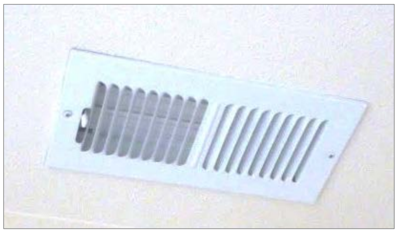
Each home has a supply diffuser in each bedroom and one in the living/dining room. The single return to the HRV originated from the ceiling at the top of the stairs in the two-story homes and from the kitchen in the one-story home. HFH elected to use standard HVAC diffusers for the HRV system rather than diffusers more appropriate for low air flow systems. Diffusers for supply and return ducts consisted of standard metal 4- × 10-in. ceiling diffuser grilles.

Supply diffusers (Figure 15) were equipped with adjustable dampers. WSU Energy Program staff advised HFH staff to consider a more appropriate diffuser for future homes. Commissioning flow measurements of the HRV system is an ESHNW program requirement but was not performed by the HVAC contractor, ESHNW verifier, or other third party. A communication breakdown apparently occurred about who was responsible for performing these measurements. Ultimately, the ESHNW verifier is responsible to ensure this requirement is met before verification. WSU Energy Program staff has communicated with the ESHNW verifier of record about this requirement and this person's responsibility to ensure the requirement is met on all future homes.

Fantech HRV

HRV duct system central splitter

Figure 14. Ventilation equipment



Typical HRV supply diffuser

Typical HRV return diffuser

Figure 15. Supply and return diffusers

All four homes used the same model HRV, which is rated to produce 105 CFM at 0.40 in. of water (100 Pa). Consequently, homes with less ductwork and fewer diffusers produced higher flow rates per diffuser than homes with more ductwork and diffusers. The number of supply diffusers per home ranged from three to six. WSU Energy Program staff using the Alnor Jr.

Balometer or The Energy Conservatory Flow Blaster powered flow hood, or both, to measure supply and return air flow measurements for Pine and Maple. Flow measurements were initially performed with diffuser dampers fully open.

Table 6 lists the individual supply and return register flow rates as measured by WSU Energy Program staff. The Maple and Larch homes were able to meet these flow rates on the lower speed assuming that either the supply or return register flow rates were required to meet Standard 62.2-2009.The return air flow in the Pine home met Standard 62.2-2013 if the Flow Blaster values were used instead of the Alnor values. High-speed operation increased the total fan wattage from roughly 62 W to 118 W.

Table 6. Measured CFM of Individual HRV Supply or Return Using Alnor Jr. and The Energy Conservatory Flow Blaster

Pine		Return	Supply						
	Speed	Top of Stairs	LVG/DNG	MBR	SE BR	SW BR	NW BR	NE BR	Total
Alnor Jr.	Low	34	<7	<7	9	8	9	9	<49
Flow Blaster		38	<10	<10	<10	<10	<10	<10	<60
Alnor Jr.	High	54	10	10	14	10	13	13	70
Flow Blaster		62	10	<10	12	<10	11	12	<65
Larch	Return	Supply							
	Speed	Top of stairs	LVG/DNG	N BR	NE BR	S BR	MBR	Total	
Alnor Jr.	Low	47	9	8	N/A	8	14	39	
Alnor Jr.	High	77	14	12	N/A	14	20	60	
Maple	Return	Supply	Total Return	Total Supply					
	Speed	Kitchen	LVG/DNG	SE BR	NE BR				
Alnor Jr.	Low	33	0	18	21	33	39		
Tru-Flo		34	0	16	18	34	34		
Alnor Jr.	High	52	0	25	29	52	54		
Tru-Flo		52	0	23	26	52	49		
Fir	Return	Supply							
Device	Speed	Top of stairs	LVG/DNG	E BR	W BR	MBR	Total		
Alnor Jr.	Low	42	13	<7	10	24	<54		
Alnor Jr.	High	64	19	12	16	33	80		

As shown in Table 6, the five-bedroom Pine home produced flow rates at some supply diffusers lower than 10 CFM due to a more extensive distribution system. These low flows are at—or less than—the minimum measurement capabilities of the Flow Blaster and the Alnor Jr. Balometer.

An estimate was made for these cases if air movement was physically observed. These locations are noted in the table with a < symbol in front of the flow rate.

One of the HRV supply diffusers at Maple was originally measured to have no flow rate. A visual inspection of the diffuser revealed no sign of airflow. The ductwork was visually inspected from the attic access and showed no sign of disconnect or blockage. WSU Energy Program staff members then closed the diffuser dampers on the home's other two supply diffusers and were able to achieve significant and measurable airflow at the diffuser. Each diffuser damper in this home was reset by WSU Energy Program staff to provide 15 CFM of supply air flow at the master bedroom diffuser and approximately 10 CFM at the other two diffusers. Guidance on how to balance room-to-air HRV airflow has been identified as a gap and may require better education and lower-flow airflow measuring tools.

The controls for the HRV are integrated into the unit as a toggle switch with two-speed capability and an off position. The HRV is plugged into a wall outlet located at roughly the same height as the HRV (5.5 ft). These controls have no labels on or near them that identify the system's function and refer occupants to operating instructions. HFH does not currently provide operating instructions that specifically refer to the operation of the system according to ASHRAE Standard 62.2 whole-building ventilation requirements.

The WSU Energy Program is working with HFH and TPU to provide better instructions for homeowners about HRV maintenance and operation and provide feedback to designers and installers. For example, Figure 16 shows an HRV where the storage shelf makes it difficult to access and change the filters. The kinked condensate drain is an installer issue. The additional HRV ductwork in the unconditioned attic was associated with the code issue (the HRV ducts are not allowed to be buried in the attic insulation at lower truss cord).

Limited access to changing filters
(homeowner issues)

Kink in condensate drain
(installer issues)

Figure 16. Problems with HRV controls

Table 7 provides information about HRV Standard 62.2 design and measured and operated flows. The green section of the table provides the ASHRAE minimum ventilation rates on high speed for both 2010 and 2013 versions. The 2013 version provides the flow rates with and without the infiltration credit that is allowed if the home has a blower door test. The final column uses the infiltration credit to compute the required runtime if the HRV was set to measured high speed (noted as the higher bolded numbers for the HRV flow in blue).

If set at high speed, Larch, Fir, and Hemlock could comply at roughly 50% runtime per hour, whereas Pine and Maple require roughly continuous operation to comply with measured high-speed rates. All the systems are operating in the continuous mode; at this setting two HRVs are operating below the Standard 62.2 requirement—Pine is operating at 63 CFM versus 49 CFM, and Maple is operating at 46 CFM versus 39 CFM measured. Standard 62.2 requirements are based on installed capacity, not as found flow measurements. In addition, the HRV balancing (or lack thereof) of the supply versus exhaust flows shows that the supply is higher for Pine and Fir, and lower for Larch and Maple. More effort and measurements from homes are needed to explore this further. In Maple, the occupants left the HRV off during the monitoring period, as shown in red text. The occupants are now operating the HRV in Maple. More investigations into the RH and energy implications for Maple are warranted in future study.

Table 8 shows the operation of the HRV by the occupants and their perception of the indoor air quality (IAQ) in their homes. It also shows the technician's perception of the IAQ as he entered the home, when he was less desensitized to odors. In Hemlock, the technician observed some cooking odors. All homeowners surveyed reported that they use their intermittent bath fans and kitchen range exhaust fans as needed. During the occupant survey, the filter changing task was discussed and filter condition checked. Most filters were in good condition. Filter changing was not seen as a significant issue. In one home, the filter access was limited by the storage shelf; in another, the condensate drain was kinked.

Table 7. HRV-Measured Flow Rates Compared to ASHRAE Standard 62.2-2013

House	2010 CFM	2013 CFM[a]	2013 CFM[b]	2013 min/h[2]	HRV Supply CFM[c]	HRV Exhaust CFM[c]	Supply/ Exhaust Balance[c]	HRV Speed	HRV Supply CFM[d]	HRV Exhaust CFM[d]	Supply/ Exhaust Balance[d]
Pine	60	87	**63**	54	70	54	1.30	Low	**49**	34	1.44
Larch	45	68	40	31	60	77	0.78	Low	39	47	0.83
Fir	60	69	43	32	80	64	1.25	Low	54	42	1.29
Hemlock	45	61	41	32	N/A	N/A	N/A	Low	N/A	N/A	N/A
Maple	45	57	**46**	53	54	52	1.04	Off	**39**	33	1.18
Alder	60	N/A	N/A	N/A	N/A	N/A	N/A	Low	N/A	N/A	N/A
Oak	45	N/A	N/A	N/A	N/A	N/A	N/A	Low	N/A	N/A	N/A
Cedar	45	N/A	N/A	N/A	N/A	N/A	N/A	Low	N/A	N/A	N/A

[a] Does not include infiltration credit
[b] Infiltration credit included with weather station factor = 0.54, Tacoma McChord Air Force Base, TMY = 742060
[c] HRV on high speed
[c] HRV on low speed

Table 8. Occupant and Technical IAQ Survey Questions

Lot	Did you use the HRV?	Occupant(s) OK with IAQ?	Technician OK with IAQ?
Pine	Yes	Very	Good
Larch	Yes	Very	Good
Fir	Yes	Very	Good
Hemlock	Yes	Don't know	Food smell
Alder	Yes	Very	Good
Oak	Yes	Somewhat	Good
Cedar	Yes	Very	Good

6 Life Cycle Cost Analysis

6.1 Cost-Effectiveness Analyses

Two approaches were used to estimate the cost-effectiveness of the DHP/ER hybrid system compared to all-ER heating:

- A simple monthly cash flow analysis based on HFH (30-year 0%-interest loan) and conventional financing (FHA type) scenario (15-year, 5%-interest loan)
- An LCCA was based on TPU energy savings derived from aggregate home energy savings analysis, utility protocols, and LCCA methodology and assumptions as required by Washington state for building code improvement assessments.

6.2 Monthly Cash Flow Economic Assumptions and Findings

A simple monthly cash flow analysis shown in Table 9 is based on HFH (30-year, 0%-interest loan) and conventional financing (FHA type) scenario (15-year, 5%-interest loan). The monthly cash flow approach is based on WSU energy savings regression analysis of individual homes. This approach has been used in BA programs to show builders and their customers the benefits of high-performance home energy-efficiency features such as DHPs. The additional monthly loan payment for the HFH homeowner financing the DHP on a 30-year, 0%-interest loan is $6.81/month ($82/year) and $13.38/month ($160.56/year) for general new homebuyers on a 15-year 5%-interest (FHA type) loan. This compares favorably with the monthly annual savings ranges for these individual homes and aggregate savings. The HFH and FHA financing scenarios shown in Table 9 indicate that new homebuyers have a beneficial monthly cash flow for the DHP/ER hybrid system in all homes in all cases ranging from $8.96–$23.26/month and $2.39–$16.69/month for HFH and FHA financial scenarios, respectively.

Table 9. Monthly Homebuyer Cash Flow Analysis for HFH and FHA Financing Scenarios

Site Energy Savings from WSU Regression Analysis	Pine El Jeffe	Larch Cottage	Fir Dbl-Front	Hemlock Cottage	Cedar Cottage	Oak Lakewood
Measured kWh Saved (WSU)	2,218	4,116	3,334	3,201	4,230	2,759
Measured $/Month Saved at $0.085/kWh	$15.77	$29.26	$23.70	$22.75	$30.07	$19.61
HFH Financing Cost; 30 year, 0%	$6.81	$6.81	$6.81	$6.81	$6.81	$6.81
Monthly Cash Flow (HfH)	**$8.96**	**$22.45**	**$16.89**	**$15.94**	**$23.26**	**$12.80**
FHA Financing Cost; 15 year, 5%	$13.38	$13.38	$13.38	$13.38	$13.38	$13.38
Monthly Cash Flow (FHA)	**$2.39**	**$15.88**	**$10.32**	**$9.37**	**$16.69**	**$6.23**
kWh = $0.0853						
Incremental Cost of DHP = $2,451						

Red denotes expense. Green denotes savings.

6.3 Life Cycle Cost Analysis Economic Assumptions and Findings

An LCCA based on TPU energy savings from aggregate home analysis uses protocols required by Washington state for building code improvement assessments. Details of this TPU LCCA analysis are found in (WSU Energy Program 2015), and a summary of the approach and results is provided in this report.

The Washington State Office of Financial Management LCCA Tool Version 2014-D was used to determine the economics of a DHP/ER hybrid heating system compared to an all-ER heating system. Modeled costs include installed initial heating system cost to the homebuyer, financing cost, maintenance cost, operating cost (electricity use), and periodic heating system replacement costs based on measure life. Monetized values are reported in net present value terms over a 50-year life cycle per the Office of Financial Management methodology. The baseline measure and the alternative measure have shorter lifetimes, which result in scheduled equipment replacement over the 50-year life cycle.

Retail rate projections are based on National Institute of Standards and Technology forecasts and assumptions per the Office of Financial Management methodology. The National Institute of Standards and Technology assumes residential real retail rates will remain relatively flat through 2035 and increase 25% by 2066. A review of the 10-year Washington state electric utility weighted annual average residential electricity rates, as archived by the Energy Information Administration, indicate that the 10-year average real rate increases are approximately 0.066%.

Financing costs were modeled with the Office of Financial Management assumptions, which include a 20% down payment, a nominal interest rate of 4.54%, and general inflation of 2.87%. Scenarios were run with 15- and 30-year mortgage terms and incremental cost scenarios from the study average to the break-even cost.

No maintenance costs were assumed for the ER zonal heating system. In general, DHPs are designed to be relatively maintenance free. This analysis assumed the homeowner would periodically clean a reusable filter; this was not included as a cost. However, this analysis assumed a $200 professional maintenance check-up/cleaning would occur over the course of the 18-year DHP measure life. The maintenance cost was modeled as an $11/year allocation toward maintenance.

Operating costs are a function of annual electric energy use measured in kilowatt-hours and a state weighted average residential retail rate per kilowatt-hour. The Energy Information Administration forms (EIA 861 4A and 4D, and EIA 861S) document the 2012 Washington state residential retail rates. From these data, a weighted average rate of $0.0853/kWh was determined and used in the analysis.

Economic results include the present value of construction, financing, maintenance, utilities, and periodic equipment replacement. Results are summarized in Table 10. The baseline all-ER zonal heated home life cycle net present value cost is approximately $22,757; the DHP/ER hybrid heating system life cycle net present value cost is $19,067. The homeowner net present value benefit of a DHP/ER hybrid heating system is estimated to be a $3,690.

Table 10. Summary of Life Cycle Cost Analysis

Alternative	Baseline All-ER Zonal System	Alternative DHP/ER Hybrid System	Change
First Construction Costs	$318	$2,722	2,403
Present Value of Capital Costs	$503	$6,700	6,198
Present Value of Maintenance Costs	$–	$473	473
Present Value of Utility Costs	$22,254	$11,893	–10,361
Total Life Cycle Cost	$22,757	$19,067	–3,690

Red denotes expense. Green denotes savings.

Using the methodology and assumptions described above, a sensitivity analysis was run by changing DHP cost assumptions ranging from $2,746 to the LCCA break-even point and mortgage terms of 30 and 15 years. These results indicate that from the homeowner's perspective, the DHP/ER hybrid heating system remains cost-effective over a wide range of installed costs. Details of this sensitivity analysis are included in WSU Energy Program (2015).

6.4 Heating, Ventilating, and Air-Conditioning Cost Data

6.4.1 Incremental First Cost Data

Two approaches were used to estimate heating system costs for the all-ER zonal heated home and the DHP/ER heating system home: one based on data provided by staff associated with the construction project and the other by an RSMeans/supplier estimation.

In the first method, the total costs and markup data for the DHP and ER heating systems were provided by HFH, the winning DHP bidder, and the Bates Technical College electrician. Based on these data, the team determined the average DHP/ER hybrid heating system cost to a homebuyer is $2,746, the average all-ER heating system cost is $321, and the resulting incremental cost is $2,425/home. This cost estimate included labor, materials, equipment, markup, and tax. Cost details are included in Appendix B.

In the second method, cost estimations based on standard HVAC/general contractor estimation practices using MEANs were compared with industry-provided cost assumptions.

These approaches were generally in agreement: $2,425 based on HFH construction data, MEAN estimation using prevailing wages, and typical HVAC and general contractor markups. Given the results, the remaining cost analysis starts with the HFH-provided cost data.

Table 11 provides a more detailed breakdown of material costs for DHP and ER zone heating of the bedrooms, as estimated by HFH staff, the electrician, and the selected bid HVAC contractor. Labor is assumed to be free for HFH, (HFH provides labor, except the HVAC contractor, at no cost as included in the DHP bid). The table shows the average HFH cost for the all-ER system with assumptions provided. The heater wiring is estimated at $0.30/linear foot, $100/bedroom heater and thermostat, and $200 for the baseboard heaters in the living room zone. The average DHP/ER hybrid cost is $2,746 and an average DHP/ER hybrid incremental cost of $2,425/home over the ER.

Table 11. Summary of Common Living Area Incremental First Costs

Cost Category	Resistance Home	Hybrid Home	Incremental Costs
Materials	$31	$23	–$8
Heating Systems	$152	$2,202	$2,050
Wiring Labor	$85	$63	–$22
Adders	$54	$58	$404
Total	$321	$2,746	$2,425

Based on these cost assessments, an incremental value of $2,425 and other incremental cost scenarios were used for the LCCA. The costs identified in this study are substantially lower than the cost of retrofitting DHPs into existing homes. Also, no HVAC subcontractor is involved in all-ER homes, because most of the work is done by the electrician and general contractor laborers.

7 Measured Results Analysis

This section summarizes the actual heating system energy use in DHP and ER modes for each house and peak load profiles. These results do not correct for any differences between periods that may influence the energy use. These differences are addressed in subsequent sections.

7.1 Actual Heating Energy Use

The actual heating electricity use for the weekly switchback periods by heating mode are shown in Table 12. The results combine all the weekly periods for the DHP or ER heating mode for each house. The heating energy use per day is presented for the common living area (DHP or ER), the bedrooms (ER), and total heating (bedrooms plus living area) for each heating mode. The average OAT and degree days per day show differences in weather between the heating modes. The period of analysis varies for each house. The reduction in electricity use in DHP mode also varies significantly for each house.

- The decrease in heating energy use from the DHP in the living area ranged from 43% to 79% with an average of 59%, suggesting a coefficient of performance around 2.
- Ideally, the ER heating energy use in the bedrooms would be similar between heating modes. This was true for two houses (Pine and Cedar), but for most houses bedroom ER energy use in DHP mode ranged from half to more than twice the energy use in ER mode. Most houses used less bedroom ER heat in DHP mode, but two used more energy, one significantly more (Larch). In ER mode, bedroom heating energy use ranged from less than 10% to 100% of living area use. In DHP mode, bedroom heating energy use ranged from about 50% to 175% of living area use. The variation in bedroom heating use suggests different operation patterns within and across houses.
- The reduction in total heating energy use in DHP mode ranged from 35% to 67%; five of the seven houses had reductions of 42%–56%. The house with the highest reduction (Alder) had the shortest analysis period, and the weather was significantly colder in ER mode than in DHP mode, indicating that the high energy reduction in this case is an outlier. Larch had a high reduction in heating energy use for the living area (78%), but also had the largest increase in bedroom ER use in DHP mode (115%), offsetting DHP savings. Hemlock is the only other house in which an increase in bedroom ER use offset the reduction in energy use in DHP mode in the living area. Pine had the lowest percentage reduction (35%). This is the largest of the seven homes, with five bedrooms. ER heat in the bedrooms accounts for a significant fraction of the load in this house.
- These simple comparisons of actual energy use do not account for differences in weather or any other factors. They do not consider changes in occupancy/use patterns for different weekly periods. The data for each house also cover different parts of the heating season. The following sections consider the influence of some of these factors on the results.

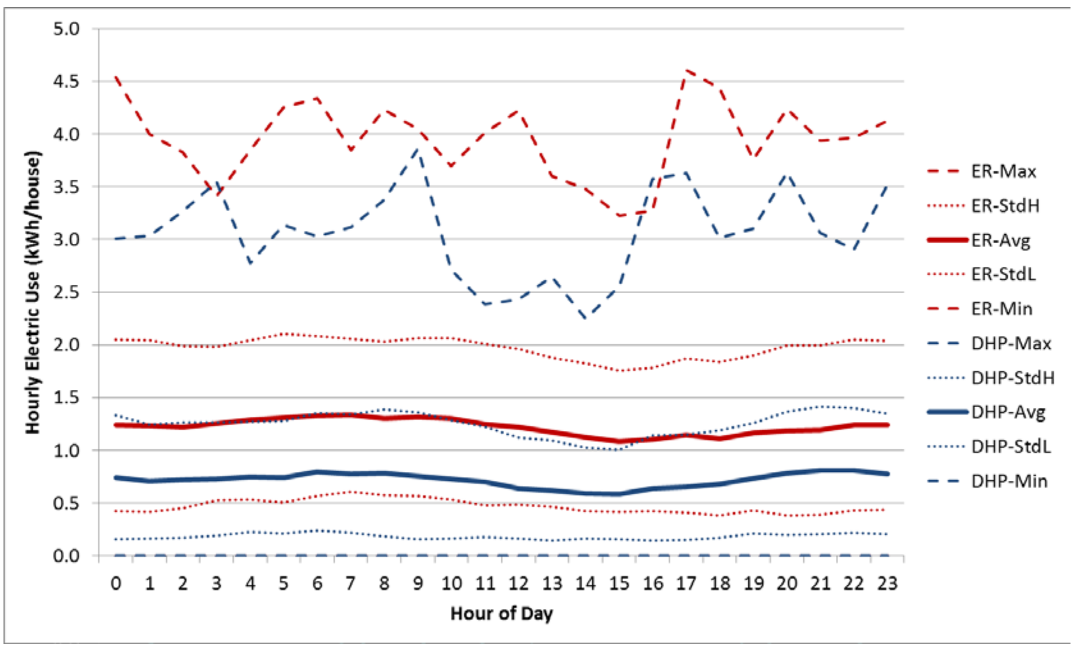
Table 12. Electricity Use by Living Room Heating Mode

House	Period	Mode	Days	Living Area (kWh/day)	Bedroom ER (kWh/day)	Total Heating (kWh/day)	Average OAT (°F)	Average Degree Days/Day (base 60°F)
Pine	9/27/2013 to 1/22/2015	ER	178	16.6	7.6	24.3	46.0	14.6
		DHP	199	8.6	7.2	15.8	47.1	13.7
		Difference	12%	–48%	–6%	–35%	2%	–6%
Larch	12/13/2013 to 1/22/2015	ER	168	19.3	3.5	22.8	48.5	12.27
		DHP	170	4.3	7.5	11.9	48.8	12.35
		Difference	1%	–78%	115%	–48%	0%	1%
Fir	11/26/2013 to 1/22/2015	ER	204	13.5	6.4	20.0	47.3	13.62
		DHP	151	6.0	2.8	8.8	48.8	12.16
		Difference	–26%	–56%	–56%	–56%	3%	–11%
Hemlock	4/15/2014 to 1/22/2015	ER	111	11.6	1.3	12.8	52.8	8.97
		DHP	105	5.7	1.8	7.4	51.2	10.02
		Difference	–5%	–51%	36%	–42%	–3%	12%
Alder	11/19/2014 to 1/22/2015	ER	29	31.6	14.3	45.9	39.2	20.75
		DHP	35	6.5	8.5	15.1	45.4	14.61
		Difference	21%	–79%	–40%	–67%	16%	–30%
Oak	12/12/2013 to 1/22/2015	ER	170	6.7	6.7	13.4	49.0	11.98
		DHP	169	3.8	3.1	6.9	48.3	12.73
		Difference	–1%	–43%	–54%	–48%	–1%	6%
Cedar	3/2/2014 to 1/22/2015	ER	134	10.4	4.0	14.4	52.5	9.05
		DHP	126	4.4	3.4	7.8	50.0	10.99
		Difference	–6%	–58%	–15%	–46%	–5%	22%
Total	Weighted average	ER	994	13.8	5.5	19.3	48.6	12.35
		DHP	955	5.6	4.8	10.4	48.6	12.31
		Difference	–4%	–59%	–13%	–46%	0%	0%

7.2 Peak Load Profile

One important consideration for electric utilities is the load profile for a DHP, which reduces electricity use and peak loads.

Figure 17 shows the combined total heating hourly load profile for the seven houses during the peak heating season (November through February). For each hour for all seven houses, the profile shows the average, the standard deviation higher and lower than the average, and maximum and minimum values for the DHP and ER living room heating modes. On average, the hourly load is about 0.5 kWh lower in DHP mode. The average load, plus or minus one standard deviation in DHP mode, ranges from 0.2 to 1.4 kWh. In ER mode, this range is 0.5–2 kWh. Peak loads in ER mode are 4.5 kWh and in DHP mode are 3.8 kWh. The profiles across the seven houses were relatively flat; individual houses may have peakier load profiles. Analysis of indoor temperature data indicated that none of the houses set back their thermostats at night, which is consistent with the load profile in the figure.



Note: ER-Min is not visible because it is covered by the DHP-Min line. At least one house has no heating energy use for every hour.

Figure 17. Hourly peak heating season load profile for the monitoried houses at The Woods

7.3 Estimates of Ductless Heat Pump Heating System Energy Savings

This section presents energy savings estimates using several approaches:

- A multivariable regression of data for all seven houses
- Variable degree day regressions for each house
- A polynomial regression of data for all seven houses.

The measured estimates of savings for each house are compared to the modeled estimates from BEopt.

7.3.1 Multivariable Regression Analysis

To control for differences in weather between heating modes, study periods across houses, and house characteristics, a multivariable regression was conducted[2] on the data for the heating season. The regression was used to verify that the type of HVAC system (ER-only or DHP/ER hybrid) had a statistically measurable impact on heating energy use. The regression equation is shown below.

- Observations that vary at the household level are represented by the subscript *h*.
- Observations that vary at the daily level are represented by subscript *t*.
- Observations that vary at both the household and daily levels have the subscript *ht*.
- The coefficient β_1 measures the average difference in daily energy use per square foot between the ER-only system and the DHP/ER hybrid system during the study period.

In addition to system type, the regression considers OAT, number of bedrooms, number of occupants, and month of the year (with a separate dummy variable for each month). A squared OAT term is included in the equation because the relationship between temperature and energy use was nonlinear.

$$kWh / ft^2_{ht} = \alpha + \beta_1 SystemType_{ht} + \beta_2 OutsideAirTemp_t + \beta_3 OutsideAirTemp_t^2 + \\ + \beta_4 Occupants_h + \beta_5 Bedrooms_h + \sum_m \beta_m Month_{mt} + \varepsilon_{ht}$$

The results of the multivariable regression show a strong statistical relationship between heating energy use and the heating system type. (see Appendix I for detailed regression output). Savings were 0.0069 kWh/ft^2 in DHP mode compared to ER mode (WSU Energy Program 2015). This results in estimated annual heating energy savings of **2,640 kWh/house** for the analysis period.

This savings estimate is for the actual weather conditions during the analysis period. Weather during this period was warmer than normal. For the nearest weather station at McChord Air Force Base,[3] the actual heating degree days for 2014 were 5,027 compared to 5,894 using TMY3 data for typical weather. However, actual heating degree days were very close to typical values for western Washington. A population-weighted average of typical western Washington heating degree days is 5,059.[4] Thus, the actual savings estimate for The Woods is a reasonable estimate for typical weather conditions in western Washington.[5] Because these houses are relatively small (average of 1,280 ft^2), savings may be higher for larger houses.

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[2] Colleagues at TPU conducted this regression analysis, which uses actual temperature data for nearby McChord Air Force Base, which was very similar to the data measured at The Woods.

[3] Measured outdoor temperatures at The Woods match McChord very closely. Heating degree days (65°F base) were 1% higher at McChord for 2014.

[4] This is based on data from the Northwest Power and Conservation Council Regional Technical Forum.

[5] Degree days in western Washington vary considerably. Rural areas further from the Puget Sound tend to be colder. Electrically heated, new-construction homes in these areas tend to show higher savings.

7.3.2 Variable Degree Day Regression Analysis

A variable degree day linear regression was conducted to estimate the annual energy savings for each house. Energy use and degree days for each weekly period were used to develop linear regressions for each heating mode and each house. Multiple regressions were conducted using different degree day base temperatures. Energy use was estimated from the regressions that had the best fit and most closely had a constant term (y-intercept) of zero.[6] No savings were estimated for Alder because coefficients of determination (R^2) for all the regressions were less than 0.7 in DHP mode and 0.4 in ER mode, producing results that were not reasonable or valid. The R^2 for all the other regressions were 0.79 or greater.

Savings were estimated using TMY3 weather data for Seattle-Tacoma International Airport and McChord Air Force Base. These weather stations were used to represent typical weather conditions for western Washington (Sea-Tac) and for The Woods (McChord).

The energy savings estimates in Table 13 range from 1,787 kWh/year to 3,254 kWh/year for Sea-Tac weather. The average annual savings is 2,410 kWh/house.[7] This is comparable to the 2,640 kWh/house from the multivariable regression analysis. Both values represent savings estimates for typical weather conditions in western Washington. Savings for McChord are significantly higher, reflecting the colder weather that is typical for this location.

The percent savings estimates for Sea-Tac weather range from 33% to 58%. Excluding the high and low values, the savings range is from 46% to 52%, which suggest savings around 50%. The weather-normalized percent savings values are consistent with the actual percent savings in Table 13. Any differences reflect cases where the actual weather was warmer or colder in DHP mode than in ER mode.

Colleagues at TPU used a polynomial regression of daily energy use versus average daily temperature to estimate energy savings for each house (WSU Energy Program 2015). Estimates were based on TMY3 weather data for Olympia (which falls between Sea-Tac and McChord). Heating savings estimates for the DHP ranged from 2,072 kWh/year to 3,692 kWh/year (excluding Alder) with an average of 2,870 kWh/year. These values fall between the results for Sea-Tac and McChord in the table. The fact that different approaches produced similar savings estimates suggests the results are robust.

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[6] A variable degree day regression approach often uses the best R^2 to select the optimum degree day base temperature. In this case, the R^2 values for different base temperatures were very similar. Because the regression is based on heating energy, energy use should be 0 for 0 heating degree days. Thus, the constant term should be 0. The regressions with a constant term closest to 0 were used to estimate the heating energy use.

[7] Accounting for square footage, the average savings is 1.906 kWh/ft^2. The average square footage for these six houses is 1,274, resulting in an annual average savings estimate of 2,427 kWh/house. Because the houses are similar in size, the impact of accounting for square footage is minimal.

Table 13. Weather-Normalized Energy Savings Estimates

House	Mode	Periods	R^2 Value	TMY Sea-Tac (kWh)	% Savings	TMY McChord (kWh)	% Savings
Pine	DHP	27	0.97	3,565		5,075	
	ER	26	0.92	5,352		7,294	
	Savings			1,787	33%	2,218	30%
Larch	DHP	27	0.84	3,157		4,449	
	ER	24	0.93	6,065		8,565	
	Savings			2,908	48%	4,116	48%
Fir	DHP	20	0.87	2,472		3,186	
	ER	22	0.88	4,612		6,520	
	Savings			2,139	46%	3,334	51%
Hemlock	DHP	15	0.89	2,534		3,343	
	ER	17	0.95	5,044		6,544	
	Savings			2,510	50%	3,201	49%
Alder	DHP	5	N/A	N/A		N/A	
	ER	5	N/A	N/A		N/A	
	Savings			N/A	N/A	N/A	N/A
Oak	DHP	27	0.79	1,778		2,371	
	ER	25	0.82	3,682		5,131	
	Savings			1,904	52%	2,759	54%
Cedar	DHP	18	0.95	2,367		3,210	
	ER	20	0.81	5,621		7,440	
	Savings			3,254	58%	4,230	57%
Average Savings					**2,417**		**3,310**

7.3.3 Polynomial Regression Analysis

The energy savings estimate used for the LCCA was based on the results of the polynomial regression performed by TPU for the report submitted to the State Building Code Council. The polynomial regression considered daily heating energy use as a function of average daily OAT using data from all the houses.

Consumption had a strong relationship to OAT for both systems (Table 14). The regressions were used to predict annual heating electricity use for the two systems for typical temperature (weather) conditions using Olympia TMY. The DHP/ER hybrid system savings was the difference in the annual estimates between the two systems in a "normal" weather year.

To determine the most conservative annual energy savings from DHPs, the heating season energy savings were reduced by cooling season energy consumption. Results of the analysis showed an average cooling season energy use for the DHP of 53 kWh, yielding an average daily cooling energy use value of 0.04 kWh/ft^2.

Table 14. Formulas Used To Predict Energy Use for Each Heating System

System Type	R^2 Value	Formula
Resistance	0.717	$kWh / ft^2 = 0.08281736 - 0.00169144 * OutsideAirTemp + 0.00000571 * OutsideAirTemp^2$
DHP/ER Hybrid	0.716	$kWh / ft^2 = 0.05568347 - 0.00140654 * OutsideAirTemp + 0.00000835 * OutsideAirTemp^2$

Applying the formulas above to OATs observed in Olympia TMY3 and deducting expected cooling energy use yielded an estimated savings of 2.19 kWh-ft^2, equivalent to **2,806 kWh** in a 1,280-ft^2 home, the average size of homes observed in this study. This energy savings value was used in the LCCA.

These savings are higher than the previous estimates largely due to the choice of Olympia TMY weather to represent the normal weather year in western Washington. Olympia is cooler than the Sea-Tac TMY weather used in the variable degree day regression analysis above. Sea-Tac more closely reflects the population-weighted average degree days in western Washington, but Olympia may better reflect weather in suburban and rural locations where new all-electric homes may be more common.

8 Measured versus Modeled Energy Use and Savings Estimates

The measured energy estimates presented in Table 13 can be compared with the modeled estimates from BEopt. The values that can most directly be compared are the estimated energy use in ER mode. The modeled and measured estimates are shown in the first two rows of Table 15. Measured energy use is higher than modeled use in all cases, particularly for Oak. In general, energy models predict higher energy use than actual use, so this is an unexpected result. It may suggest that these homes are high heating energy users.

Table 15. Modeled and Measured Energy Use and Savings Estimates

Scenario Type and DHP Space Heat Displacement Site Energy	Pine El Jeffe	Larch Cottage	Fir Double-Front	Hemlock Cottage	Alder Double-Front	Cedar Cottage	Oak Lakewood
Case A: 100% ER (heat kWh)	5,111	4,666	3,722	5,484	4,637	4,660	1,964
Measured ER	7,294	8,565	6,520	6,544	N/A	7,440	5,131
Case B: 100% DHP (heat kWh)	1,043	1,061	923	1,172	953	982	378
Case A minus B (heat kWh) DHP/ER Hybrid	**4,068**	**3,605**	**2,799**	**4,312**	**3,684**	**3,678**	**1,596**
Measured Savings Estimate	2,218	4,116	3,334	3,201	N/A	4,230	2,759
Estimated ER Displacement	70%	67%	86%	86%	81%	76%	77%
Modeled Savings Estimate	2,862	2,418	2,405	3,722	2,998	2,809	1,230
Case A minus B ($/year @0.0853/kWh)	$347	$308	$239	$368	$314	$314	$136

BEopt is a single-zone model, so it cannot model DHP heat in the living area and ER heat in the bedrooms. It can only model 100% DHP heat. To estimate modeled energy savings, the estimated ER displacement by the DHP (from measured data) was multiplied by the case A minus B savings (100% ER-100% DHP). This approach assumes a linear relationship between 100% ER and 100% DHP energy use. This is probably not true, but it allows approximate estimates of modeled energy use to be made. In general, the modeled energy savings estimate for each house does not match very well with the measured savings. The average modeled savings estimate is 2,636 kWh/year/house; the average measured savings estimate is 3,310 kWh/year/house.

8.1 Other Factors Influencing Energy Savings

Occupant behavior influenced the energy savings from the DHP system. To better understand other factors influencing energy savings, indoor temperature and RH measurements are compared in ER and DHP modes, occupant survey responses are summarized, and cooling energy use is analyzed.

8.1.1 Indoor Temperature and Relative Humidity

Household occupants were asked to maintain comfortable indoor temperatures during the research period. To identify any differences in indoor thermal comfort, indoor temperatures and RHs were measured in the main living area, master bedroom, and a second bedroom. Figure 18 presents indoor temperatures for the living area for each house in ER and DHP modes.[8] Generally, comfortable temperatures were maintained and temperatures were comparable between heating modes, but there were some differences:

- Three houses had lower living area temperatures in DHP mode, but this difference was less than 1°F lower except for Larch.
- Four houses had higher living area temperatures in DHP mode. The temperature in DHP mode was 3°F higher for Fir, 1.9°F higher for Alder, and 1.3°F higher for Oak. All three of these houses had lower bedroom ER heating use in the DHP mode, suggesting the households were trying to reduce bedroom ER use with the DHP.

Figure 19 and Figure 20 present the indoor temperatures for the master bedroom and second bedroom, respectively. Temperatures tend to be lower in the bedrooms than in the living area. The indoor temperatures between the ER and DHP heating modes are more similar than they are for the living area. In only one case—the second bedroom in Fir—was the average temperature more than 1°F different between modes. Although Table 12 shows variation in bedroom ER energy use between modes, no evidence emerged to suggest this impacted temperatures or comfort in the bedrooms.

[8] The box plots show the 25th to 75th percentiles in the box with the median at the point where the colors shift in the box. The whiskers show the minimum and maximum temperatures excluding outliers.

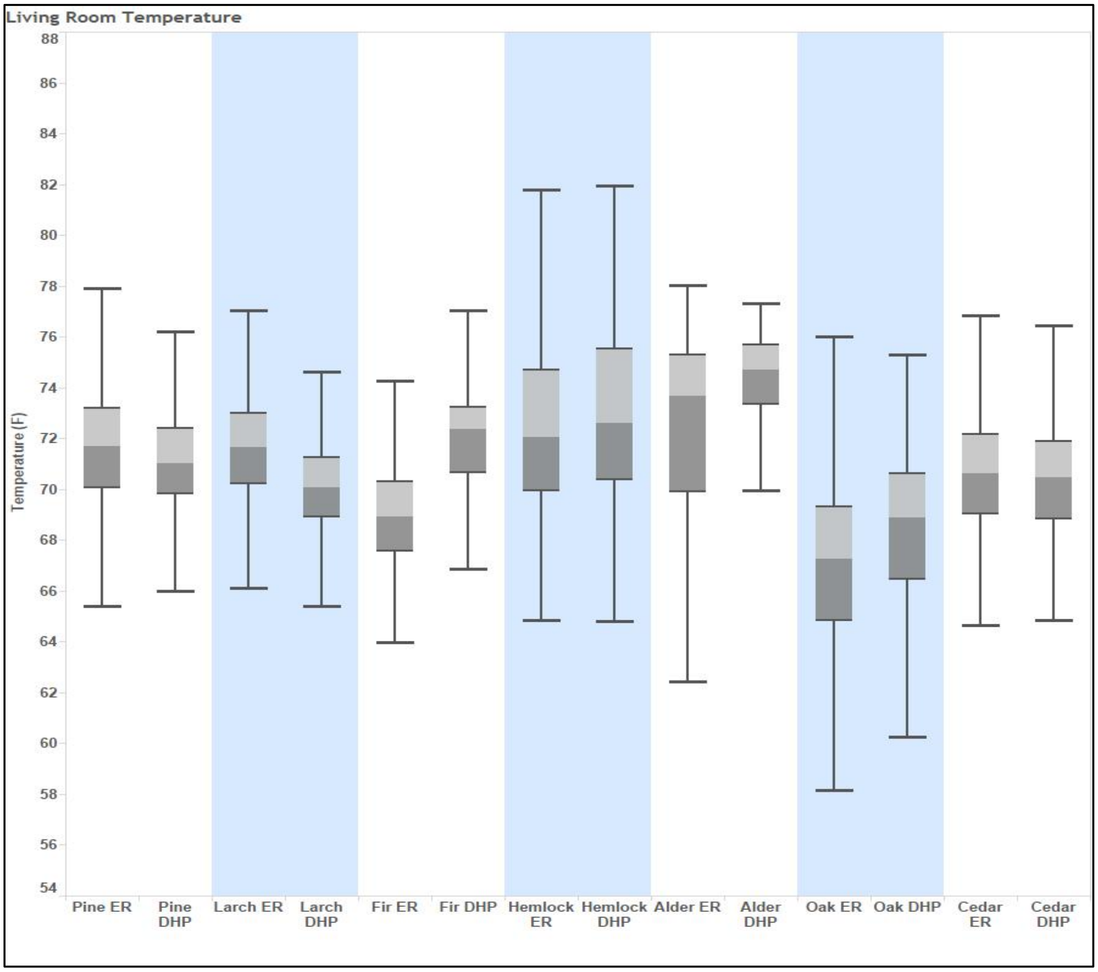

Figure 18. Living area indoor temperatures for each house in ER and DHP heating modes

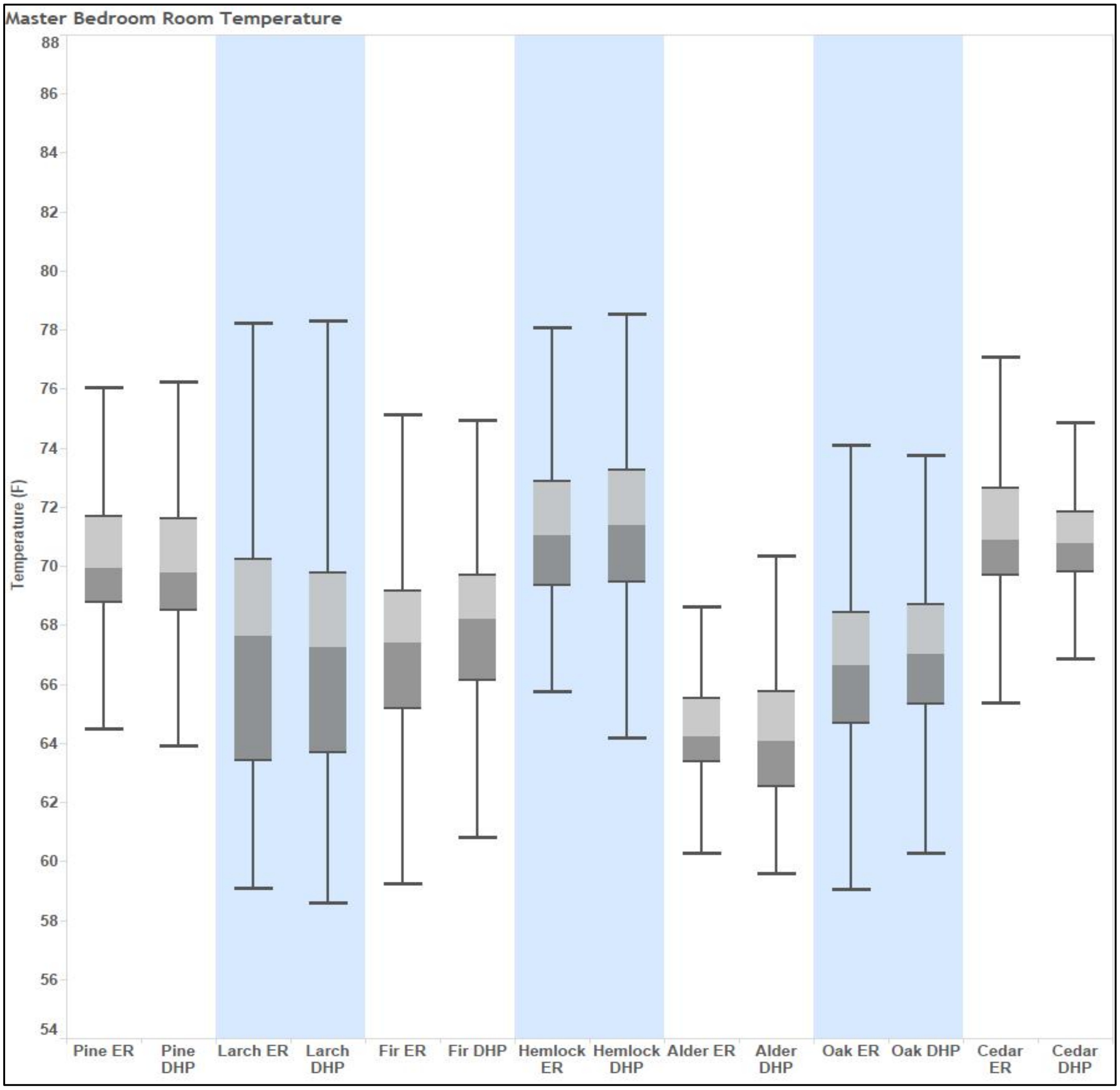

Figure 19. Master bedroom indoor temperatures for each house in ER and DHP heating modes

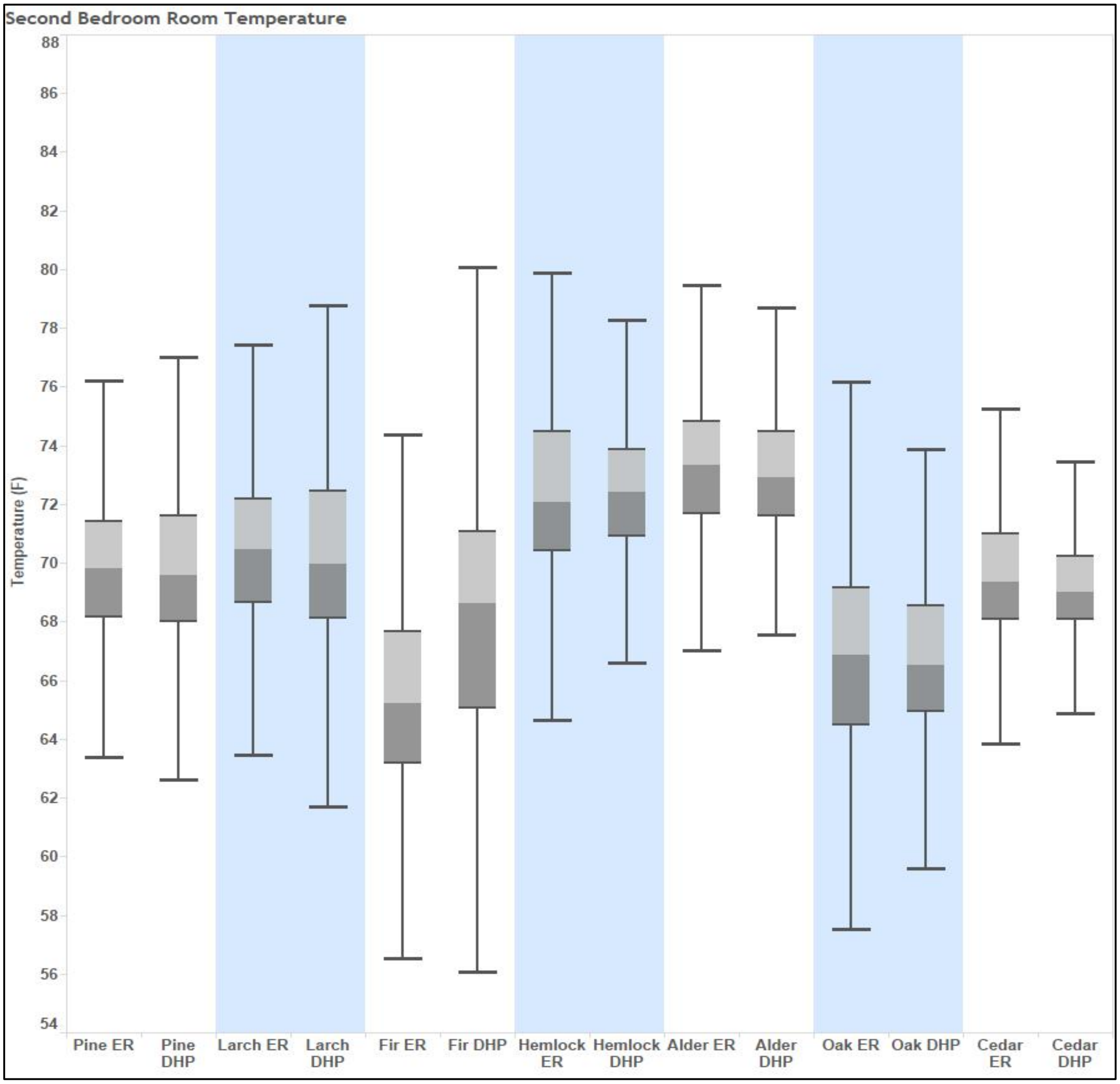

Figure 20. Second bedroom indoor temperatures for each house in ER and DHP heating modes

Table 16 shows RH in the living area. The RHs in the houses were generally at comfortable levels—between 40% and 60%. Alder tended to have lower RH levels, which may be due to the short data collection period during the winter from November to January (when outdoor air moisture levels are lower). RH levels in DHP and ER modes were very similar. RH in the bedrooms was similar to the living area, but tended to be slightly higher due to lower indoor temperatures in the bedrooms. These homes have ventilation systems, so moisture levels should be the same regardless of the heating mode.

Table 16. Living Area RH by Living Room Heating Mode

House	Period	Mode	Days	Maximum (%)	+1 Standard Deviation (%)	Average (%)	–1 Standard Deviation (%)	Minimum (%)
Pine	9/27/2013 to 1/22/2015	ER	178	80.1	61.4	52.2	43	32.2
		DHP	199	81.3	62	53	44.1	27.5
		Difference	–12%	1.2	0.6	0.8	1.1	–4.7
Larch	12/13/2013 to 1/22/2015	ER	168	83.9	59.9	48.2	36.6	25.3
		DHP	170	88.4	61.8	50.1	38.4	18.5
		Difference	–1%	4.5	1.9	1.9	1.8	–6.8
Fir	11/26/2013 to 1/22/2015	ER	204	85.2	57.5	49.2	41.0	25.9
		DHP	151	75.5	58.6	48.4	38.2	20.7
		Difference	26%	–9.7	1.1	–0.8	–2.8	–5.1
Hemlock	4/15/2014 to 1/22/2015	ER	111	71.1	58.7	49.8	40.9	16.5
		DHP	105	73	59.2	49.3	39.3	23.8
		Difference	5%	2	0.5	–0.5	–1.6	7.3
Alder	11/19/2014 to 1/22/2015	ER	29	56.8	43.2	36.2	29.1	19.3
		DHP	35	55	43.5	37.8	32.1	19.5
		Difference	–21%	–1.8	0.3	1.6	3.0	0.2
Oak	12/12/2013 to 1/22/2015	ER	170	80.1	63.6	52.4	41.2	21.5
		DHP	169	75.1	62.5	50.1	37.6	15.0
		Difference	1%	–5	–1.1	–2.3	–3.6	–6.5
Cedar	3/2/2014 to 1/22/2015	ER	134	68.8	55.7	47.7	39.7	22.6
		DHP	126	69.3	57.9	48.2	38.6	25.6
		Difference	6%	0.6	2.2	0.6	–1.1	3

8.1.2 Occupant Survey Results

Household occupants were interviewed in early 2015 to learn about differences in behavior between heating modes and to ask about their satisfaction with the two heating systems. In some cases their responses—along with observations by the survey team—help explain the energy savings results.

- Pine may have had lower total heating savings because it is the largest house, with five bedrooms and two stories. ER heat in the bedrooms accounts for a larger portion of the heating load. The interviews indicated that bedroom doors were closed most of the time, which reduces the ability of DHP heat to offset ER heat in the bedrooms. Also, a cabinet in the living area partially blocked the DHP, which may affect the distribution of heated air, diminishing DHP performance.
- Larch had one of the highest DHP savings (78%), but it also had the highest increase in bedroom ER energy use in DHP mode. During the survey, the occupant said that in ER mode the indoor air was hotter than in DHP mode. However, the interviewer observed that the DHP thermostat was set very low. The temperature data for the living area in Figure 18 show lower temperatures in DHP mode for Larch, which helps explain the high DHP savings for the living area. The high bedroom ER use in DHP mode may be an attempt to compensate for this.
- Occupants in only two houses, Oak and Cedar, indicated during the interview that they behaved differently in DHP mode than ER heating mode. The primary differences were lowering the bedroom thermostats and keeping the bedroom doors open. This would allow the DHP to displace a larger fraction of the ER heating load. ER energy use in the bedrooms was lower in DHP mode for both houses, which is consistent with this observation. The weather-normalized percent energy savings were also highest for these two houses (52% and 58% in Table 13), suggesting their behavior change did make a difference.
- In two other houses, the bedroom ER use suggests differences in behavior between heating modes, but the occupants did not mention this in the interviews. Occupants were asked to operate their homes to maintain comfort, and the indoor temperature data indicate this occurred. Baseboard thermostats are not highly accurate devices, and unless an occupant never changes settings, the settings were probably not identical between modes. In the living area the thermostat of the DHP (which shows temperature) cannot be precisely set to maintain the same indoor temperature as the ER baseboard thermostat (which shows a comfort range). Perceptions of comfort for these two heating systems even at the same temperature also may be different. Occupants set the thermostats to values that suited them.

At the end of the research period, occupants could pick which of the two heating systems they wanted to keep. Six of the seven households picked the DHP. The reasons included the availability of cooling (4), better heating performance (3), more furniture placement options (2), and safety concerns about the ER heat (1). One occupant was unsure which system to pick and wanted more information about the energy savings from the DHP and maintenance and replacement costs.

When asked specifically about the heating performance of the DHP, the occupants of three households rated it better than the ER heat, three rated it the same, and one rated it worse (Larch). The low rating by Larch occupants may be due to low temperature settings. Two households said the DHP distributed heat less evenly than the ER system and one household said it heated less quickly. All other households said the DHP performed as well as or better than the ER system in these two areas.

The households tended to view the DHP as slightly noisier than the ER system. Only one household rated the DHP as quieter. Three households said both systems were very quiet. Three households felt the DHP was a little noisier than the ER system.

Six of seven households indicated the temperature controls for the ER system were very easy to use and five of seven gave the same rating for the DHP. Only one household said the DHP controls were very difficult to use. However, the comments suggest the occupants were using only the most basic temperature controls for the DHP and had not tried to use the programming features.[9] Although they seemed happy with the basic controls, they may have expressed different opinions about ease of use if they had tried the programming features. Greater use of the programming features could result in more DHP energy savings.

Regarding summer use of the DHP, three households said they often used the DHP for cooling, two said they sometimes used it for cooling, and one said they did not use the DHP in the summer. The other house was not occupied during the summer. All five households that used cooling said the DHP performed very well in cooling mode.

8.1.3 Cooling Energy Use

The DHP provides both heating and cooling. Compared to an ER heating system with window air conditioners, the DHP system is more efficient. However, at The Woods the DHP is being compared with an ER system that provides only heating, not cooling. Although AC in the Northwest is becoming more common, most houses still do not have AC. Thus, cooling energy use can be viewed as reducing the DHP energy savings.

The living room heating system operated only in DHP mode from July 11 to Sept. 14, 2014 so residents had access to cooling. DHP energy use for cooling before or after this summer period may have occurred but was likely minimal. Washington occasionally has hot periods during the day immediately before or after the summer period, but mornings and evenings are usually cool. Households should have been operating the DHP in heating mode only except during the summer.

Energy use of the DHP during the summer period was relatively low (Table 17), ranging from 18 to 115 kWh. There were 143 cooling degree days during this period (for a base temperature of 70°F), suggesting the need for cooling was relatively low.

[9] This observation is very consistent with research on programmable thermostat use that suggests many people use the manual temperature controls and do not program their thermostats.

Table 17. Summer Period DHP Energy Use (July 11–Sept. 14, 2014)

House	Energy Use (kWh)	Survey Cooling Use	Average OAT (°F)	Maximum OAT (°F)	Cooling Degree Days (base 70°F)
Pine	48	Sometimes	66	95	143
Larch	18	Never			
Fir	115	Often			
Hemlock	76	Often			
Alder	N/A	Sometimes			
Oak	30	Sometimes			
Cedar	31	Often			

The results in Table 17 confirm the survey responses: households with the highest summer period energy use said they used the DHP for cooling "often" (Fir, Hemlock, and Cedar); the household with the lowest use (Larch) reported never using the DHP for cooling. The exception is Cedar, where the measured energy use was more like the "sometimes" users than the "often" users.

Not all the energy use during the summer period was for cooling. Nights and mornings can be cool and DHP energy was used at OATs lower than 65°F during the summer period. Energy use for heating was low, but it may be 25% or more of the summertime energy use for some houses. The need for morning heating during the summer may be due to the house being cooled the previous day (cooling-induced heating).

The intermittent energy use of the DHP during the summer is illustrated in Figure 21. Analysis of data in the cooling season did not show a relationship between OAT and energy use for all the houses together. DHP energy use was intermittent for most of the houses. However, this same figure for the highest summer user (Fir) does show a correlation between OAT and energy use.

Another consideration is the differences in comfort between the houses during the summer period. Fir, with the highest summer DHP energy use, had an average living area temperature during the summer of 70°F, plus or minus 1.9°F (one standard deviation) and a maximum temperature of 77.6°F. The corresponding values for Larch (lowest summer DHP use) were 73.8°F, ± 2.1°F, and a maximum of 79.5°F. Living area temperatures for the rest of the houses mostly fell between these values. Even with little or no cooling, Larch maintained interior temperatures lower than 76°F most of the time, reflecting the fact that these are well-insulated houses.

As occupants become accustomed to having cooling over time, summer energy use may increase. However, energy use for even the highest user was modest (less than 5% of the DHP savings estimate) and comfort levels were reasonable, even for the houses with low cooling use.

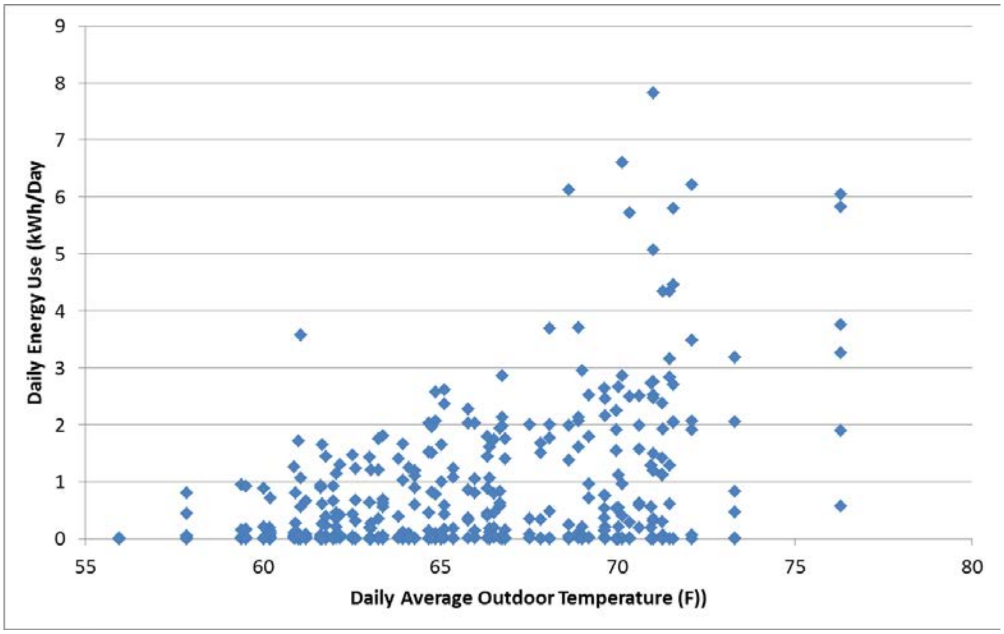

Figure 21. Daily summer energy use by OAT

9 Conclusions/Lessons Learned

This section evaluates this research in light of the research questions, discusses the lessons learned, and identifies gaps. Heating electricity use was analyzed for the weekly switchback periods for the heating season. Future analysis should look more closely at the relationship between electricity use and outdoor-indoor temperature differences and occupant behavior (e.g., door closures and bedroom thermostat use) to estimate annual electricity use and DHP savings under typical weather conditions.

Q1 – What are the average annual electricity and bill savings of a DHP/ER hybrid heating system compared to the alternative all-electric resistance system in this study of HFH homeowners in a Pacific Northwest climate?

The results are slightly lower than estimated. The weather-normalized annual energy savings from the DHP/ER hybrid system were 2,806 kWh. Using a 2016 weighted average state residential electricity rate of $0.0853/kWh, average annual bill savings is $239. Site-specific savings ranged from a low of 2,019 kWh to about 4,289 kWh. These are the savings estimates used for the life cycle cost analysis.

Q2 – What are the estimated total and incremental installed costs of DHP/ER hybrid zonal heating systems in new-construction single-family homes?

The average DHP/ER hybrid heating system cost to a new-home HFH buyer is $2,746. The average cost for an all-ER heating system is $321, which results in an incremental cost of $2,451 per home.

Q3 – What is the average expected life cycle and consumer monthly cash flow impact of a DHP/ER hybrid heating system compared to an all-ER heating system?

The homes studied are expected to have a 2015 present value positive benefit of $3,690 with a DHP/ER hybrid heating system compared to an all-ER heating system. This analysis assumes DHP replacement every 18 years and minor service costs over the 50-year analysis period.

The monthly cash flow is positive. The additional monthly payment is $6.81/month ($82/year) for the HFH homeowner financing the DHP on a 30-year 0% interest loan and $13.38/month ($160.56/year) for general new homebuyers on a 15-year 5% interest (Federal Housing Administration [FHA] type) loan. HFH and FHA financing scenarios indicate that new homebuyers have a beneficial monthly cash flow for the DHP/ER hybrid in all homes in all cases of $8.96–$23.26/month for an HFH financing scenario and $2.39–$16.69/month for an FHA financial scenario.

Q4 – How do the measured energy use and DHP savings compare with the BEopt model when field information about the home and occupants is known?

BEopt estimated heating energy use and savings varied considerably with the monitored results. In ER mode where modeled and measured results can be directly compared, measured energy use was higher than modeled energy use in all cases. BEopt is a single-zone model, so it cannot model a DHP/ER hybrid heating system that has two heating zones. DHP savings was estimated from the 100% DHP case and the estimated ER displacement by the DHP. Annual savings estimates ranged from 1,230 kWh to 3,722 kWh. These estimates were comparable to the range of measured savings, but the measured and modeled savings estimates for particular houses varied significantly.

Q5 – Are participants at least as comfortable with DHP systems as with zonal electric systems, and what occupant behavior parameters may impact energy savings or thermal comfort or both?

At the end of the research period, households had the option of picking which of the two heating systems they wanted to keep. Six of the seven household picked the DHP. The reasons included the availability of cooling (4 households), better heating performance (3 households), more furniture placement options (2 households), and safety concerns about the ER heat (1 household). One household was unsure which system to pick and wanted more information about the energy savings from the DHP and maintenance and replacement costs.

Q6 – What air-conditioning impact is associated with the DHP?

The energy use of the DHP during the summer period (July 11–Sept. 14, 2014) when cooling was enabled was relatively low (18–115 kWh in the seven houses). This air conditioning represents a small cooling load, which is a small percentage (2.5% for the highest user) of the total space-conditioning load for these homes.

Q7 – What were the measured hourly indoor temperature and RH conditions in each switchback mode?

In the living area temperatures were generally 68°–74°F and RH was 40%–60%. Temperatures tended to be lower in the bedrooms with slightly higher humidity levels. The conditions in the bedrooms vary only slightly between modes.

Q8 – What are the lessons learned during the design, construction, and verification commissioning phases of the project?

The WSU Energy Program team identified gaps in code jurisdiction and volunteer stakeholder education and training that were associated with the design, installation, inspection, and commissioning issues. Subsequently, the team proposed solutions to address envelope tightness and heat recovery ventilator (HRV) effectiveness. The team also identified gaps associated with the building official and fire marshal codes that have challenged HFH’s ability to build tight and ventilate right in terms of HRV design and sprinkler insulation/air-sealing requirements and ceiling insulation installation/HRV attic ducting details. Better coordination and ongoing dialogue with code inspectors, fire marshals, and HFH are recommended to help HFH improve on the “build tight and ventilate right” philosophy in future homes in this and other HFH communities.

The results of this effort have already been used by utility stakeholders in a code change proposal to the Washington State Building Code Council (WSU Energy Program 2015).

If this proposal is adopted as expected in 2016, Washington would have the first state energy code to require at least one DHP head in all new electrically heated single-family and low-rise multifamily homes.

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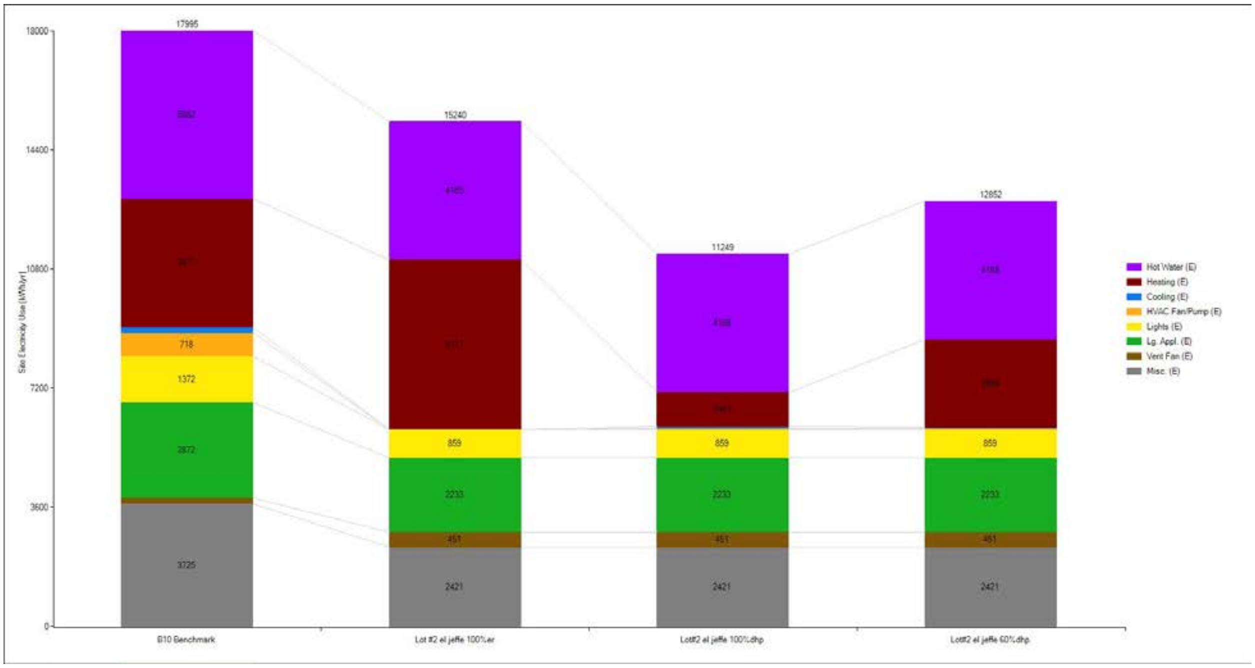
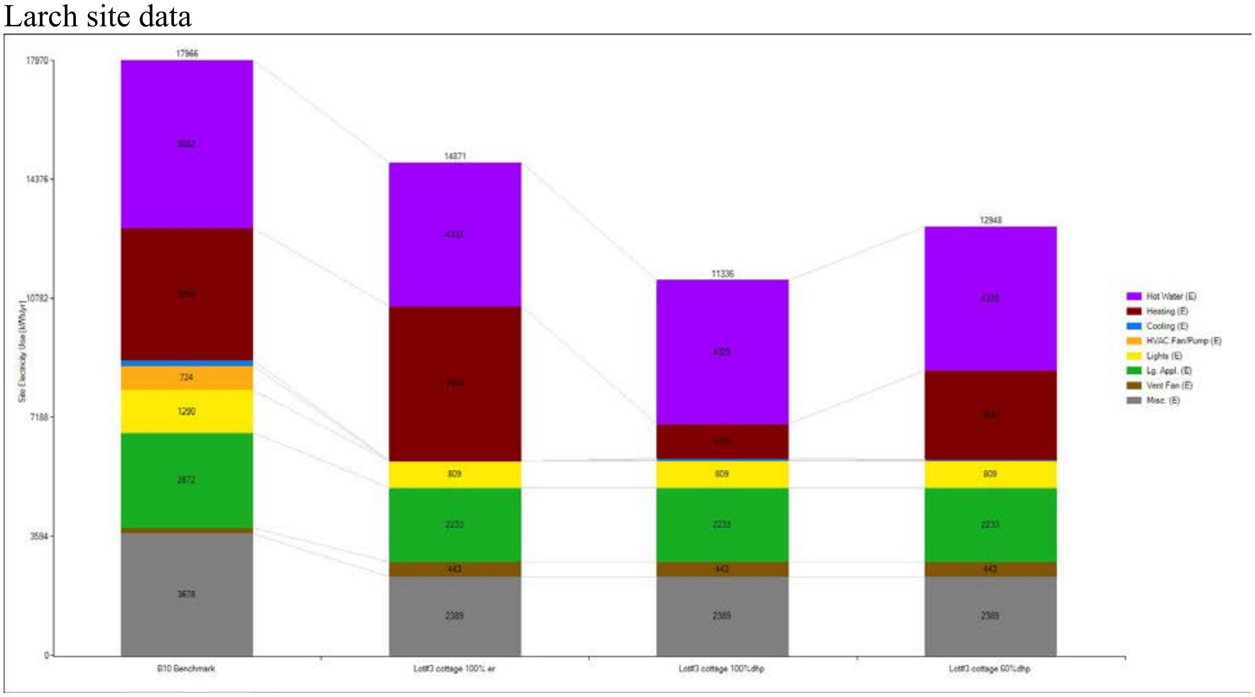
Appendix A: Building Energy Optimization Files—Simulation Results

The BEopt data files can be found in the NREL BA Field Data Repository database.

Pine site data



Larch site data



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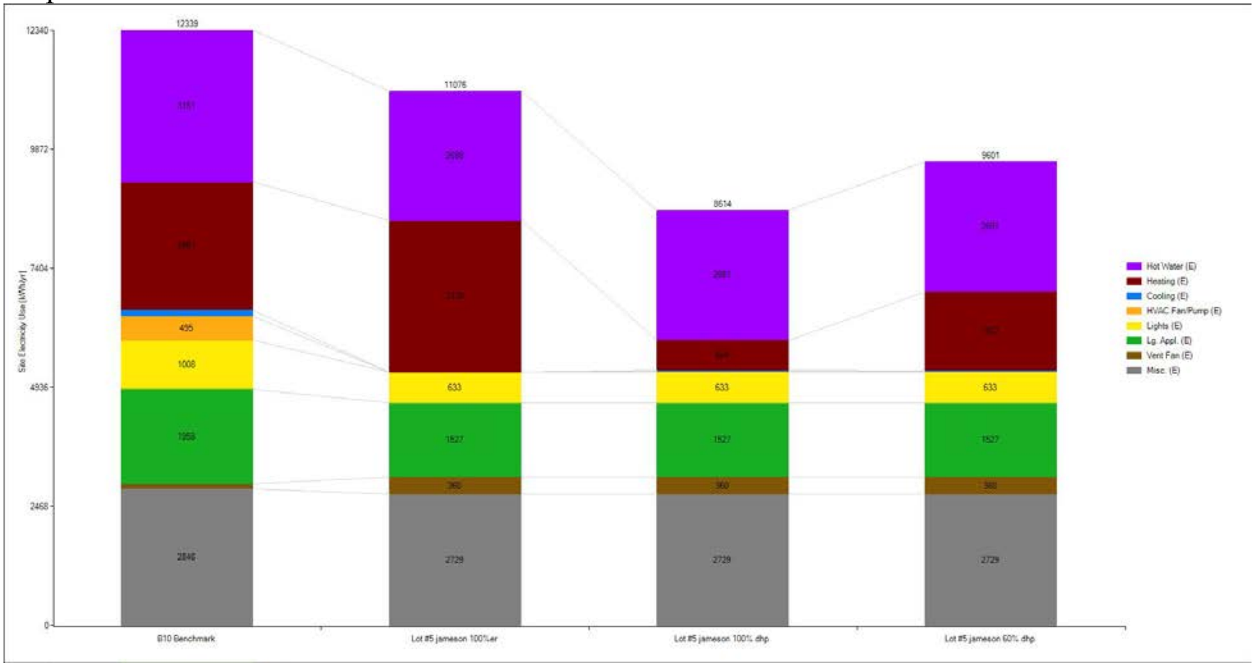
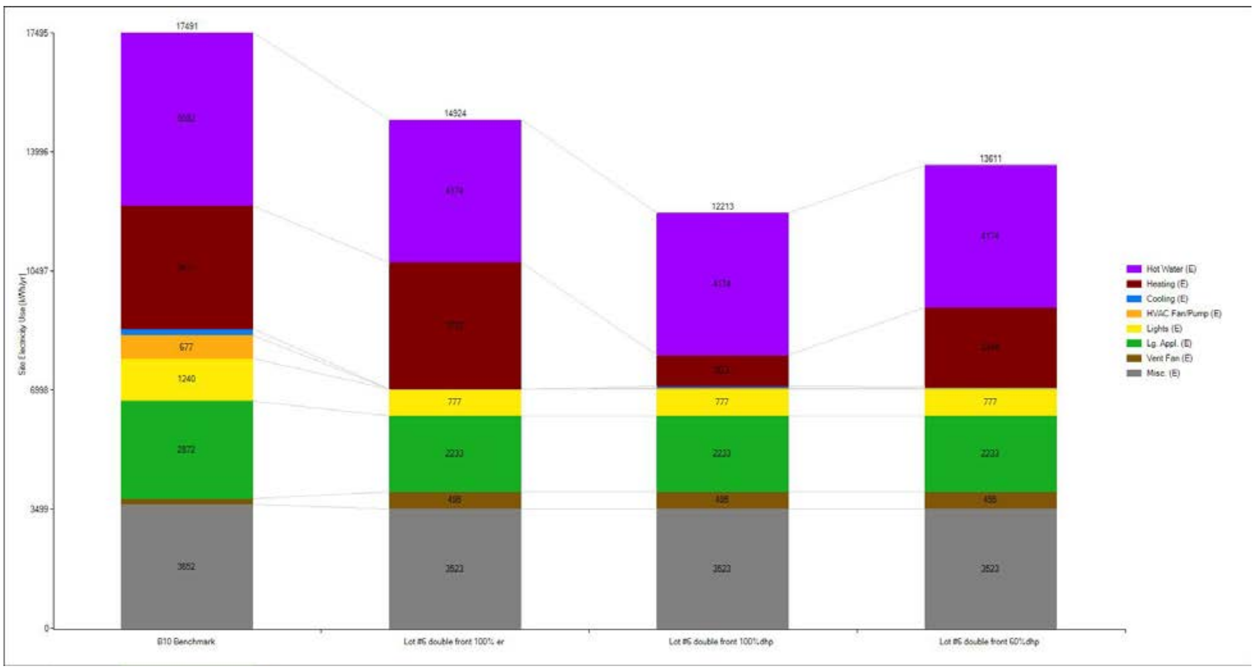
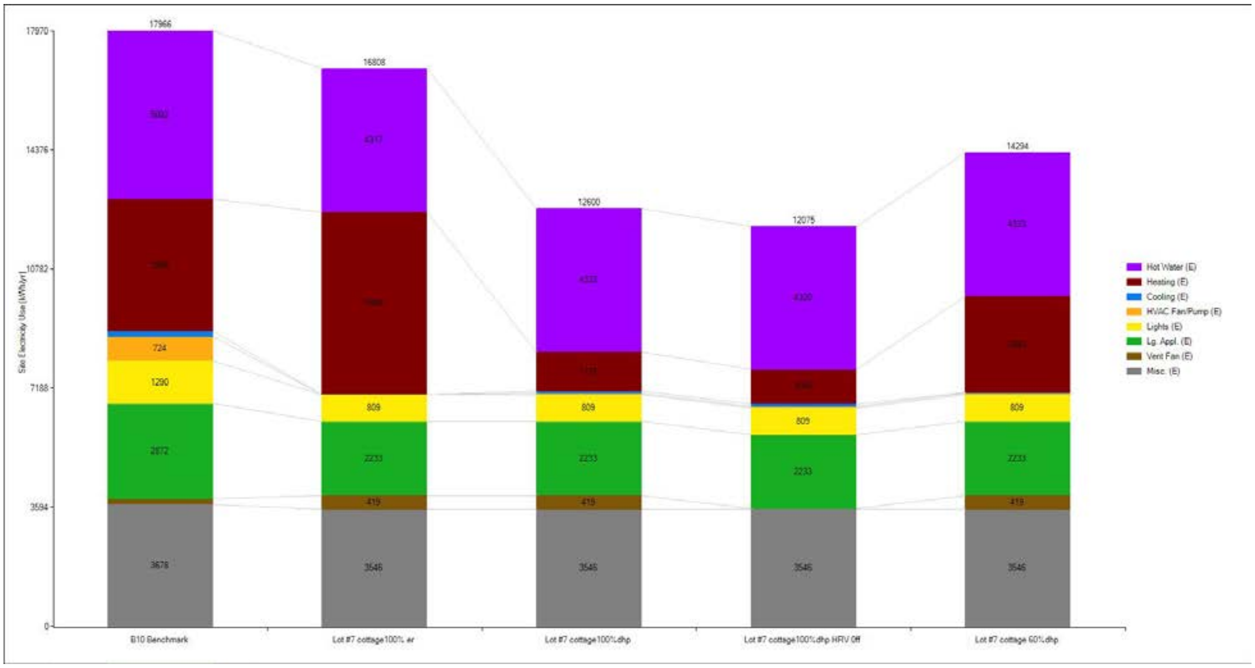
Maple site data



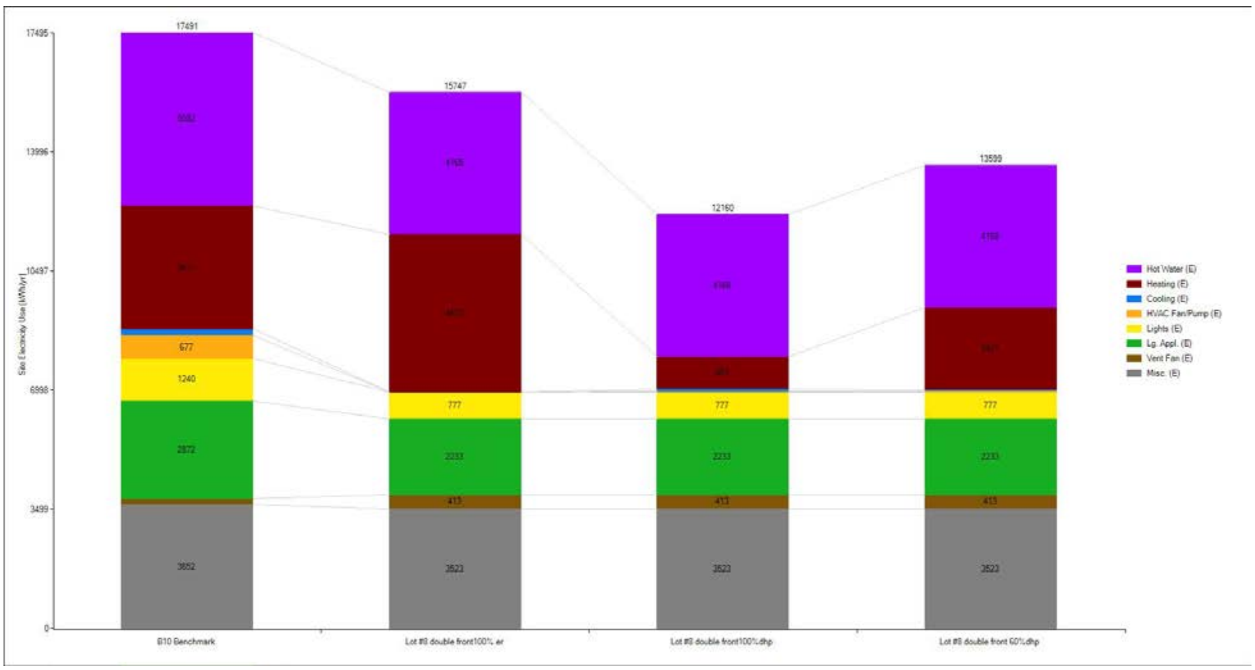
Fir site data



Hemlock site data



Alder site data



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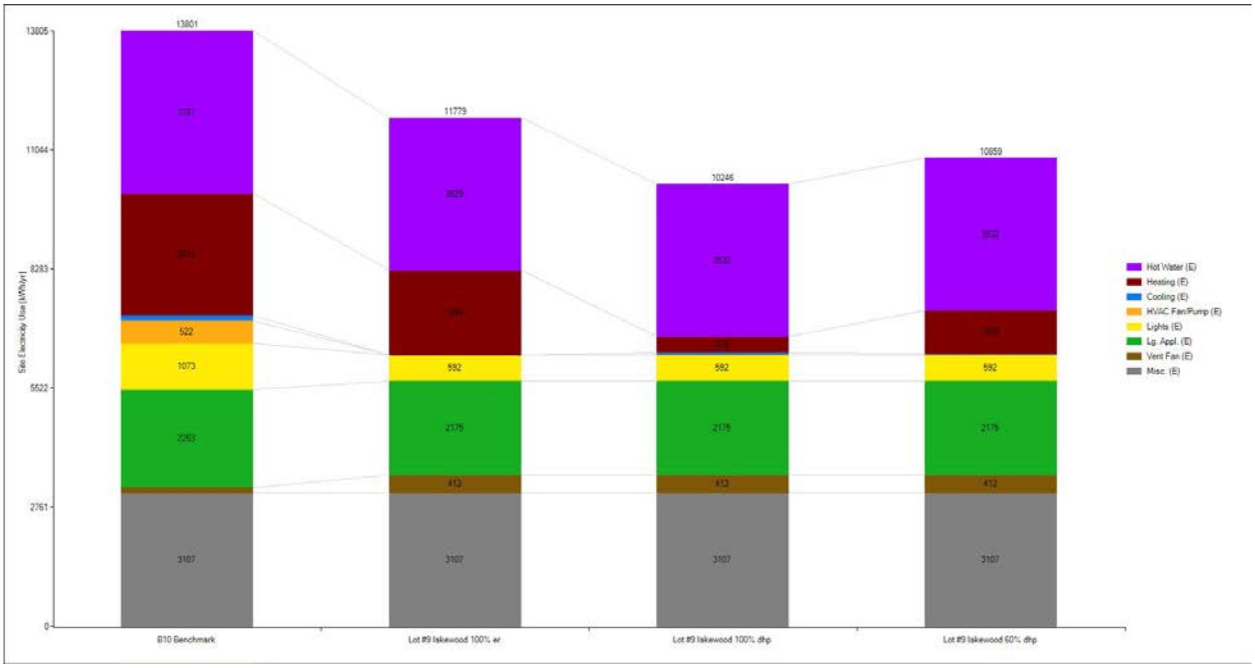
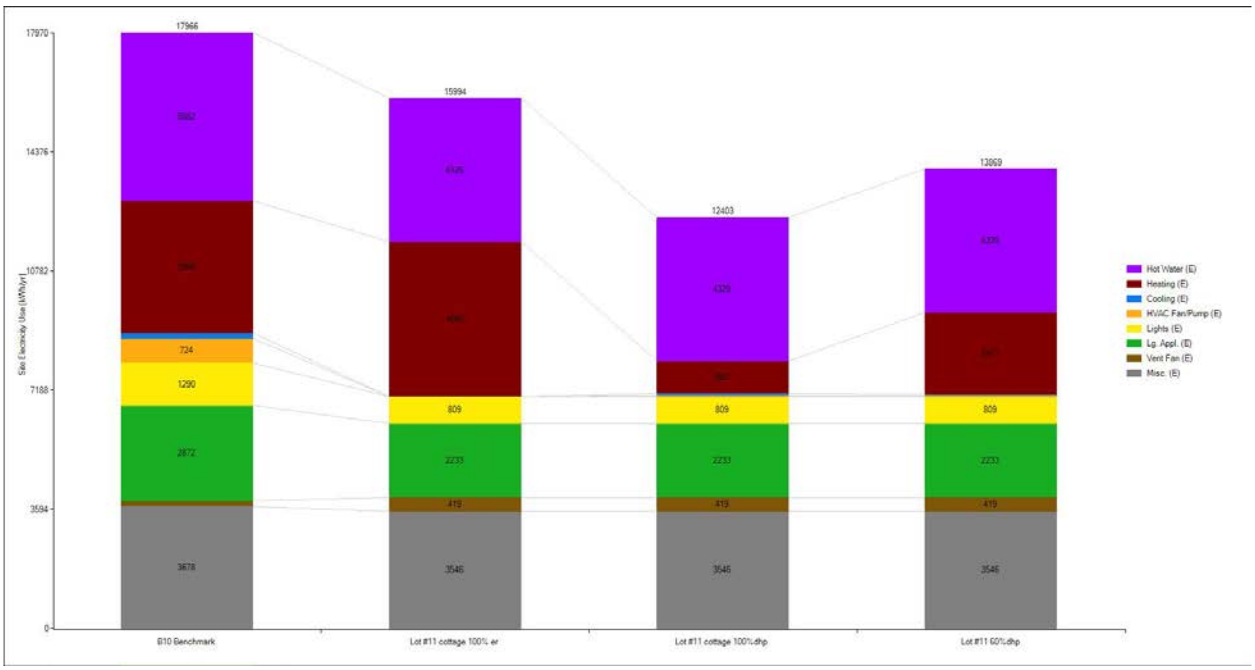
Oak site data



Cedar site data



Appendix B: Ductless Heat Pump Bids and Electric Resistance Costing Discussion

HFH staff estimated the average hours per system, based on the installation of the first four systems, at 12 h/system. HFH estimated the additional materials cost to be $400/system. A summary of the bids is provided in Table 18, with the winning bidder cost at $1,577/system plus $400 in additional material costs to HFH.

Table 18. Summary of DHP Bids

Bidder Code and Option(s)	Manufacturer/ Brand	SEER	HSPF	Heat at 47°F (Btu/h)	HFH per Unit with 9.5% Sales Tax	HFH Materials ($)
1	Mitsubishi MUZ-GE24N	—			$2,517	$400
2a	Mitsubishi FE12	23	10.6	13,600	$2,685	$400
2b	LG Premier 12	26	11.5	13,600	$2,639	$400
2c	Gree EVO+18	18	10	13,600	$2,454	$400
3a	Fujitsu AOU12RLFW	23	11	19,100	$1,980	$400
3b (won bid)	Fujitsu AOU12RL2	16	9	16,000	$1,577	$400

HFH and TPU collected bids based on a Request for Proposals for Provisions of Ductless Heat Pumps and Support Services for The Woods at Golden Given by Habitat for Humanity. Three companies bid six options. These bids included providing all DHP outdoor units, wall-mounted units, and line sets and covers, and included a 5-year parts/7-year compressor warranty. The bids also included the installation by an Environmental Protection Agency-certified refrigeration technician to connect refrigeration lines, check integrity of the refrigeration circuit and charge the system, and provide HFH with general technical assistance during the design and installation phases. HFH provided all additional labor and materials associated with the system, including:

- Obtaining electrical and mechanical building permits
- Installing indoor and outdoor units
- Installing electrical power supply circuits and running and connecting other electrical systems
- Installing line set covers and running refrigeration line sets
- Installing condensate management
- Air sealing and weatherproofing of all building penetrations
- Tape wrapping or otherwise protecting exposed line-set insulation.

Bid #1 (not selected)

- Mitsubishi Mr. Slim MUZ-GE24N; 2-ton outdoor unit, 2-ton wall-mounted unit, line sets, and cover 30 systems × $2,100 each = $63,000.
- Materials: outdoor unit, wall mounted unit, line sets and covers
- Does not include pad, condensate drain, electrical work, or electrical and mechanical permits:
- Labor: 30 systems × $200/system = $6,000
- Verify flared line set connection, nitrogen pressure test of line set, system evacuation, holding below 500 microns for 5 minutes, refrigeration added or removed to installation specifications.
- Total $69,000 + $6,555 (9.5% sales tax) = $75,555, or **$2,517 per system**

Includes Mitsubishi Diamond Contractor 7-year parts warranty on indoor and outdoor units, labor warranty on refrigeration only.

Bid #2

- Materials include: outdoor unit, wall mounted unit, line sets, and covers.
- Does not include concrete pad, condensate drain, electrical work, or electrical and mechanical permits.
- Labor included in bid: 30 systems to Environmental Protection Agency-certified refrigeration technician to connect refrigeration line check integrity of the refrigeration circuit and charge the system

Option 1:

- Mitsubishi Mr. Slim FE12 (1.0 ton indoor and outdoor unit)
- 30 systems x $2,452 each = $73,575 + $6,990 (9.5% sales tax) = $80,565 or **$2,685 per system**
- SEER 23, HSPF 10.6 = 13,600 Btu/h @ 47°F, 8,300 Btu/h @ 17°F

Includes Mitsubishi limited warranty 5 years on parts and defects, 7 years on compressor

Option 2:

- LG Premier 12 (1-ton indoor and outdoor unit)
- 30 systems x× $2,410 each = $72,300 + $6,969 (9.5% sales tax) = $79,169 or $2,639 per system
- SEER 26, HSPF 11.5 = 13,600 Btu/h @ 47°F

Includes 5 year parts, 7 years on compressor

Option 3:

- Gree Evo+ 18; HSPF = 10, SEER = 18 (1.5-ton indoor and outdoor unit)
- 30 systems × $2,241 each = $67,230 + $6,387 (9.5% sales tax) = $73,616 or **$2,454/system**
- SEER 18, HSPF 10 = 18,800 Btu/h @ 47°F

No warranty information provided with bid.

Bid #3 (Selected)

- Materials: outdoor unit, wall mounted unit, line sets, and covers
- Labor included in bid: 30 systems to Environmental Protection Agency-certified refrigeration technician to connect refrigeration lines, check integrity of the refrigeration circuit and charge the system
- Does not include pad, condensate drain, electrical work, or electrical and mechanical permits:

Includes 5 year parts, 7 years on compressor

Option 1:

- Fujitsu AOU12RLFW; 1-ton outdoor unit, 2-ton wall mounted-unit, line sets, and cover
- 30 systems × $1,808 each = $54,240 + $5153 (9.5% sales tax) = $59,393 or $1,980 per system
- SEER 23, HSPF 12.5 = 19,100 Btu/h @ 47°F, Heating Operating Range = 15° to 75°F

Option 2 (Selected)

- Fujitsu 12RL2; 1-ton outdoor unit, 2-ton wall-mounted unit, line sets, and cover
- 30 systems × $1,440 each = $43,200 + $4,104 (9.5% sales tax) = $47,304 or **$1,577 per system**
- SEER 16, HSPF 9 = 16,000 Btu/h @ 47°F, heating operating range = 5° to 75°F

An estimate of the cost for a non-HFH new-construction scenario to a building contractor without permit costs is $4,000, with a rough breakdown as follows:

- Fujitsu RLS2 @ $2,014 + 15-ft line set @ $184 + line set cover @ $90 = $2,228
- Pad, blocks, gravel, and hardware @ $190 + electrical subcontractor @ $1,100 DHP = $1,290
- Install labor (excluding electrical) = $485 (6 to 8 hours)

ER Cost Estimates

HFH estimated average costs for installing:

- Fan-assisted, zonal thermostat controlled (750-W Cadet) resistance heaters in bedrooms at $100 each. HFH electrician labor (based on 30 seconds per linear foot of heating wire) is estimated at 1.7–2.6 hours for the installation for an all-electric home and 1–1.7 hours for the DHY Hybrid home (with no living room baseboards). Material costs were assumed to be $0.30/linear foot of 220 heater wiring.
- Zonal thermostat controlled (two 1,250-W baseboard) resistance heaters in the main living area at $200 each as part of the switchback testing. HFH estimated the labor cost at 0.4 to 0.9 hours to install. Material costs were assumed to be $0.30/linear foot of 220 heater wiring.

Table 19 provides the end-load results of BEopt modeling. A heating thermostat setting was selected based on the HOBO logger data average temperature in all zones during the heating season, for both the ER and the DHP modes. For cooling, a 76°F set point was used in all cases.

Table 19. New Construction Installation Cost Estimates

NEW CONSTRUCTION INSTALLATION COST ESTIMATION

ELECTRIC RESISTANCE SYSTEM HOMES

Lot Numb	House Plan Type	1 or 2 Sto	Bedroom Coun	House ft2	Lineal Feet LI	BR	BR	BR	BR	BR	Tot	w/o L	220V Wire Materials ER Run $ Total	w/o LI	LR onl	ER Heaters $ LR	BR	ER Total Material $ Tota	w/o L	LR onl	220V Wire Labor hrs Tota	w/o L	LR	Labor $ Total	w/o LI	LR onl	Total ER GC Installed Cost Total	w/o LR	LR	Total ER GC Installed Price Total	w/o LR	LR
2	El Jeffe	2	5	1391	140	46	44	57	30	22	339	199	$ 102	$ 60	$ 42	$ 152	$ 657	$ 910	$ 716	$ 194	2.8	1.7	1.2	$ 283	$ 166	$ 117	$ 1,192	$ 882	$ 310	$ 1,431	$ 1,058	$ 373
3	Cottage	2	3	1267	104	42	27	56			229	125	$ 69	$ 38	$ 31	$ 152	$ 394	$ 614	$ 431	$ 183	1.9	1.0	0.9	$ 191	$ 104	$ 87	$ 805	$ 536	$ 270	$ 966	$ 643	$ 324
6	Double-Front	2	4	1316	80	76	51	22			229	149	$ 69	$ 45	$ 24	$ 152	$ 525	$ 746	$ 570	$ 176	1.9	1.2	0.7	$ 191	$ 124	$ 67	$ 936	$ 694	$ 242	$ 1,124	$ 833	$ 291
7	Cottage	2	3	1267	104	42	27	56			229	125	$ 69	$ 38	$ 31	$ 152	$ 394	$ 614	$ 431	$ 183	1.9	1.0	0.9	$ 191	$ 104	$ 87	$ 805	$ 536	$ 270	$ 966	$ 643	$ 324
8	Double-Front	2	4	1316	80	76	51	22			229	149	$ 69	$ 45	$ 24	$ 152	$ 525	$ 746	$ 570	$ 176	1.9	1.2	0.7	$ 191	$ 124	$ 67	$ 936	$ 694	$ 242	$ 1,124	$ 833	$ 291
9	Lakewood	1	3	1133	118	32	13	48			210	92	$ 63	$ 28	$ 35	$ 152	$ 394	$ 609	$ 422	$ 187	1.7	0.8	1.0	$ 175	$ 77	$ 98	$ 783	$ 498	$ 285	$ 940	$ 598	$ 342
11	Cottage	2	3	1267	104	42	27	56			229	125	$ 69	$ 38	$ 31	$ 152	$ 394	$ 614	$ 431	$ 183	1.9	1.0	0.9	$ 191	$ 104	$ 87	$ 805	$ 536	$ 270	$ 966	$ 643	$ 324
12	Lakewood	1	3	1133	88	32	13	48			180	92	$ 54	$ 28	$ 26	$ 152	$ 394	$ 600	$ 422	$ 178	1.5	0.8	0.7	$ 150	$ 77	$ 73	$ 749	$ 498	$ 251	$ 899	$ 598	$ 302
	Average	1.8	3.5	1261	102	48	32	46	30	22	234	132	$ 70	$ 40	$ 31	$ 152	$ 460	$ 682	$ 499	$ 182	2.0	1.1	0.9	$ 195	$ 110	$ 85	$ 877	$ 609	$ 268	$ 1,052	$ 731	$ 321
	Max	2	5	1391	140	76	51	57	30	22	339	199	$ 102	$ 60	$ 42	$ 152	$ 657	$ 910	$ 716	$ 194	2.8	1.7	1.2	$ 283	$ 166	$ 117	$ 1,192	$ 882	$ 310	$ 1,431	$ 1,058	$ 373
	Min	1	3	1133	80	32	13	22	30	22	180	92	$ 54	$ 28	$ 24	$ 152	$ 394	$ 600	$ 422	$ 176	1.5	0.8	0.7	$ 150	$ 77	$ 67	$ 749	$ 498	$ 242	$ 899	$ 598	$ 291

HYBRID HEATING SYSTEM HOMES

Lot Number	House Plan Type	1 or 2 Story	Bedroom Count	House ft2	Lineal Feet LR	BR1	BR2	BR3	BR4	BR5	Total	w/o LR	20V Wire Materials Hybrid Run Total	w/o LR	LR only	Hybrid Heaters $ LR	BR	Hybrid Total Material $ Total	w/o LR	LR only	220V Wire Labor hrs Total	w/o LR	LR	Labor $ Total	w/o LR	LR only	Total Hybrid GC Installed Cost Total	w/o LR	LR	Total ER GC Installed Price Total	w/o LR	LR
2	El Jeffe	2	5	1391	110	46	44	57	30	22	309	199	$ 93	$ 60	$ 33	$ 1,702	$ 657	$ 2,451	$ 716	$ 1,735	2.6	1.7	0.9	$ 258	$ 166	$ 92	$ 2,709	$ 882	$ 1,827	$ 3,250	$ 1,058	$ 2,192
3	Cottage	2	3	1267	74	42	27	56			199	125	$ 60	$ 38	$ 22	$ 1,702	$ 394	$ 2,156	$ 431	$ 1,724	1.7	1.0	0.6	$ 166	$ 104	$ 62	$ 2,321	$ 536	$ 1,786	$ 2,786	$ 643	$ 2,143
6	Double-Front	2	4	1316	50	76	51	22			199	149	$ 60	$ 45	$ 15	$ 1,702	$ 525	$ 2,287	$ 570	$ 1,717	1.7	1.2	0.4	$ 166	$ 124	$ 42	$ 2,453	$ 694	$ 1,759	$ 2,943	$ 833	$ 2,110
7	Cottage	2	3	1267	74	42	27	56			199	125	$ 60	$ 38	$ 22	$ 1,702	$ 394	$ 2,156	$ 431	$ 1,724	1.7	1.0	0.6	$ 166	$ 104	$ 62	$ 2,321	$ 536	$ 1,786	$ 2,786	$ 643	$ 2,143
8	Double-Front	2	4	1316	50	76	51	22			199	149	$ 60	$ 45	$ 15	$ 1,702	$ 525	$ 2,287	$ 570	$ 1,717	1.7	1.2	0.4	$ 166	$ 124	$ 42	$ 2,453	$ 694	$ 1,759	$ 2,943	$ 833	$ 2,110
9	Lakewood	1	3	1133	88	32	13	48			180	92	$ 54	$ 28	$ 26	$ 1,702	$ 394	$ 2,150	$ 422	$ 1,728	1.5	0.8	0.7	$ 150	$ 77	$ 73	$ 2,300	$ 498	$ 1,802	$ 2,760	$ 598	$ 2,162
11	Cottage	2	3	1267	74	42	27	56			199	125	$ 60	$ 38	$ 22	$ 1,702	$ 394	$ 2,156	$ 431	$ 1,724	1.7	1.0	0.6	$ 166	$ 104	$ 62	$ 2,321	$ 536	$ 1,786	$ 2,786	$ 643	$ 2,143
12	Lakewood	1	3	1133	88	32	13	48			180	92	$ 54	$ 28	$ 26	$ 1,702	$ 394	$ 2,150	$ 422	$ 1,728	1.5	0.8	0.7	$ 150	$ 77	$ 73	$ 2,300	$ 498	$ 1,802	$ 2,760	$ 598	$ 2,162
	Average	1.8	3.5	1261	76	48	32	46	30	22	208	132	$ 62	$ 40	$ 23	$ 1,702	$ 460	$ 2,224	$ 499	$ 1,725	1.7	1.1	0.6	$ 173	$ 110	$ 63	$ 2,397	$ 609	$ 1,788	$ 2,877	$ 731	$ 2,146
	Max	2	5	1391	110	76	51	57	30	22	309	199	$ 93	$ 60	$ 33	$ 1,702	$ 657	$ 2,451	$ 716	$ 1,735	2.6	1.7	0.9	$ 258	$ 166	$ 92	$ 2,709	$ 882	$ 1,827	$ 3,250	$ 1,058	$ 2,192
	Min	1	3	1133	50	32	13	22	30	22	180	92	$ 54	$ 28	$ 15	$ 1,702	$ 394	$ 2,150	$ 422	$ 1,717	1.5	0.8	0.4	$ 150	$ 77	$ 42	$ 2,300	$ 498	$ 1,759	$ 2,760	$ 598	$ 2,110
	Hybrid vs ER Heating System Incremental Cost or Price															$ 1,550	$ -	$ 1,542	$ -	$ 1,542	$ (0)	$ -	$ (0)	$ (22)	$ -	$ (22)	$ 1,521	$ -	$ 1,521	$ 1,825	$ -	$ 1,825

Notes

1. Cells highlighted in orange are data entry cells
x. GC General Contractor
2. LR Living Room
3. BR Bed Room 1,2,3,4,5
4. ER Electric Resistance
5. LF Lineal Foot
6. Living room electric resisitance heaters are two, 4' 1.25 kW baseboad heaters controlled by zonal thermostat. Living room wire and wire labor cost reflect the longer runs for the two separate heaters.
7. Bedroom electric resistance heaters are one, cadet type heater with wall mounted thermostat per bedroom. An additional 30 feet labor cost is assumed to install line voltage thermostats for ER zonal heaters.

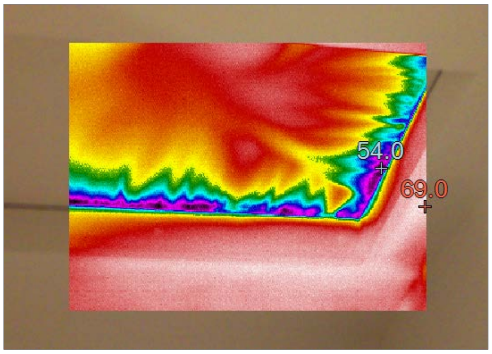
Calculations

8. 220V Wire Materials for ER Run $: Lineal Feet X Materials Cost per LF
9. ER Heaters $: Living Room Heater Cost + (Bedroom Count X Bedroom Cadet ER Heater Cost
10. Home Owner Costs: General Contractor Cost X (1 + markup)

Bates-HFH Cost Data	
Labor rate/hour	$ 100
Labor hrs (30 sec/LF)	30
Materials ($0.30/LF)	$ 0.30
DHP site prep and installation @ 2 hours	$ 100
DHP Convenience Outlet and connection to outdoor unit	$ 25
Bedroom Cadet ER Heater Cost w/wall mount stat	$ 131
Living Room Baseboard ER Heaters Cost w/wall mount stat	$ 152
1-Head DHP Cost (includes commissioning and tax)	$ 1,577
2-Head DHP Cost (includes commissioning and tax)	[illegible]
Builder Market Assumptions	
Percent Assumed General Contractor Mark-Ups	20%

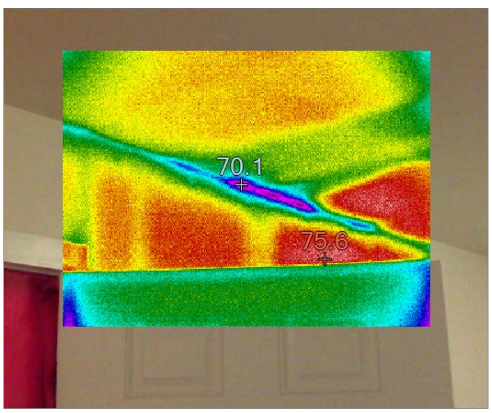
Average Estimated Hybrid vs ER Heating System GC Incremental Cost	$ 1,521
Average Estimated Hybrid vs ER Heating System Incremental Home Owner Cost	$ 1,825

Appendix C: Photos of Infrared from Fluke/Washington State University Air (Quality Assurance) Training

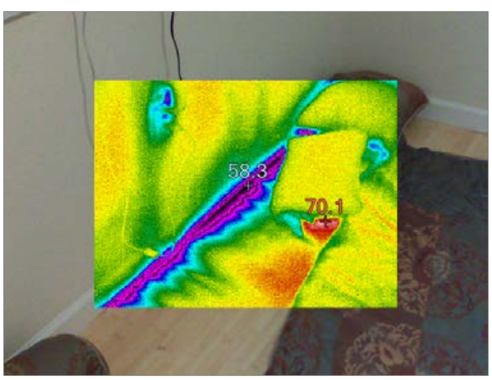


This IR image shows significant air leakage at the attic access hatch while the building was less than –50 Pa of induced depressurization.

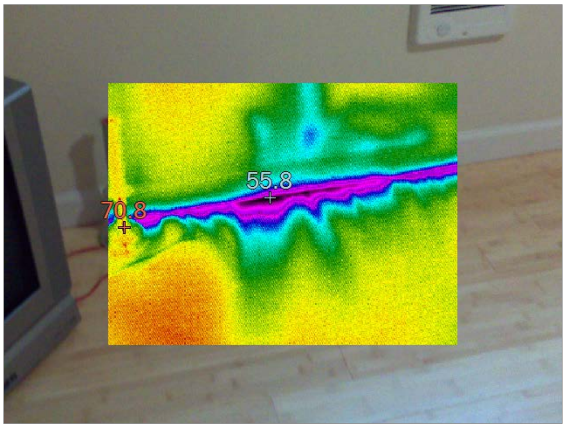
Attic access hatch showing ineffective air sealing at attic access hatch.



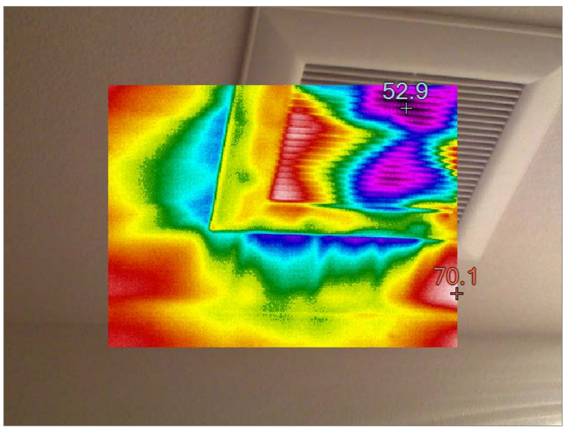
Front porch roof truss-to-wall intersection heat loss.



Air leakage at base plate. House depressurized to –50 Pa at time of image.



Air leakage at base plate. House depressurized to –50 Pa at time of image.

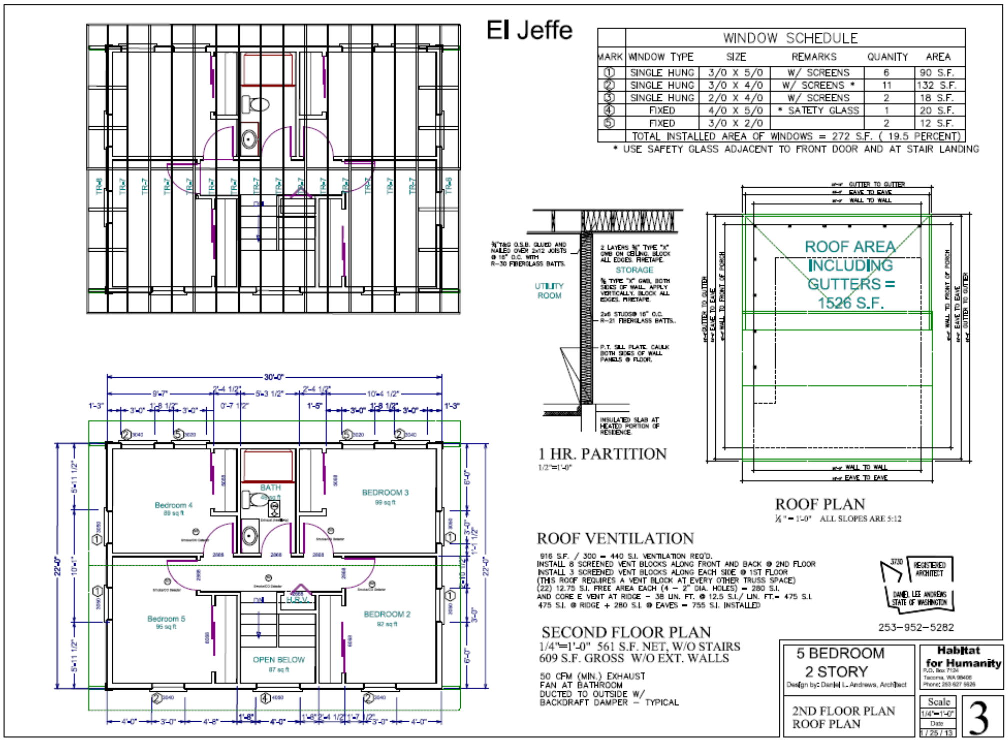


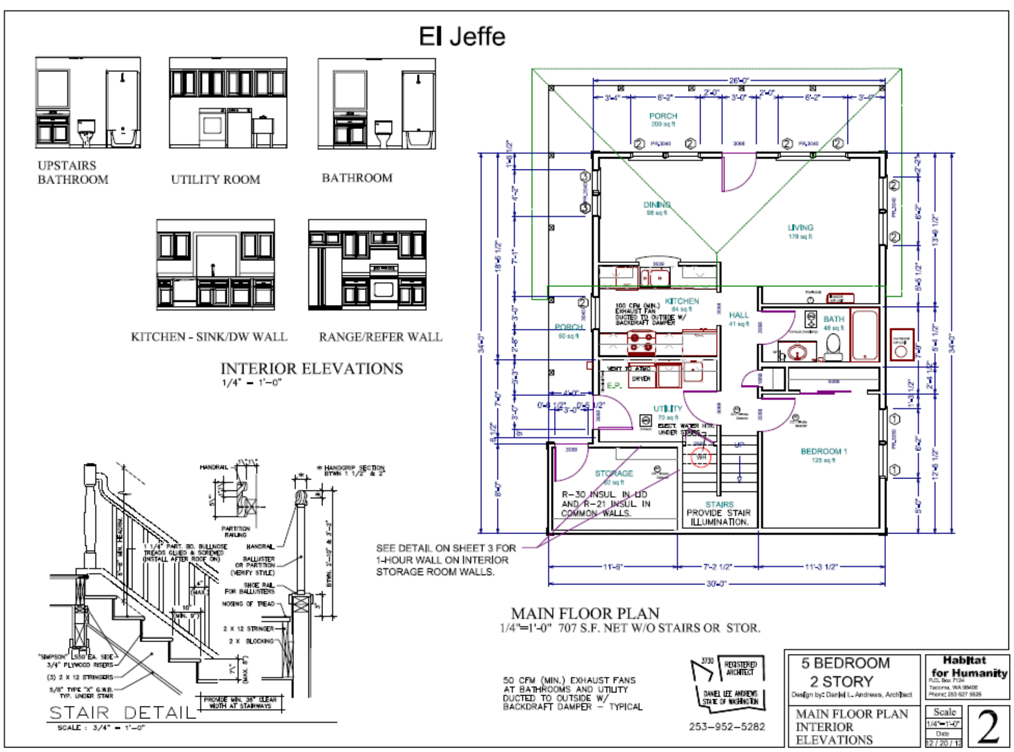
Air leakage at bathroom exhaust fan. Further investigation revealed the fan housing was not anchored correctly or sealed.

Fluke staff training HFH QA staff in the use of IR thermography to locate air leaks and insulation voids.

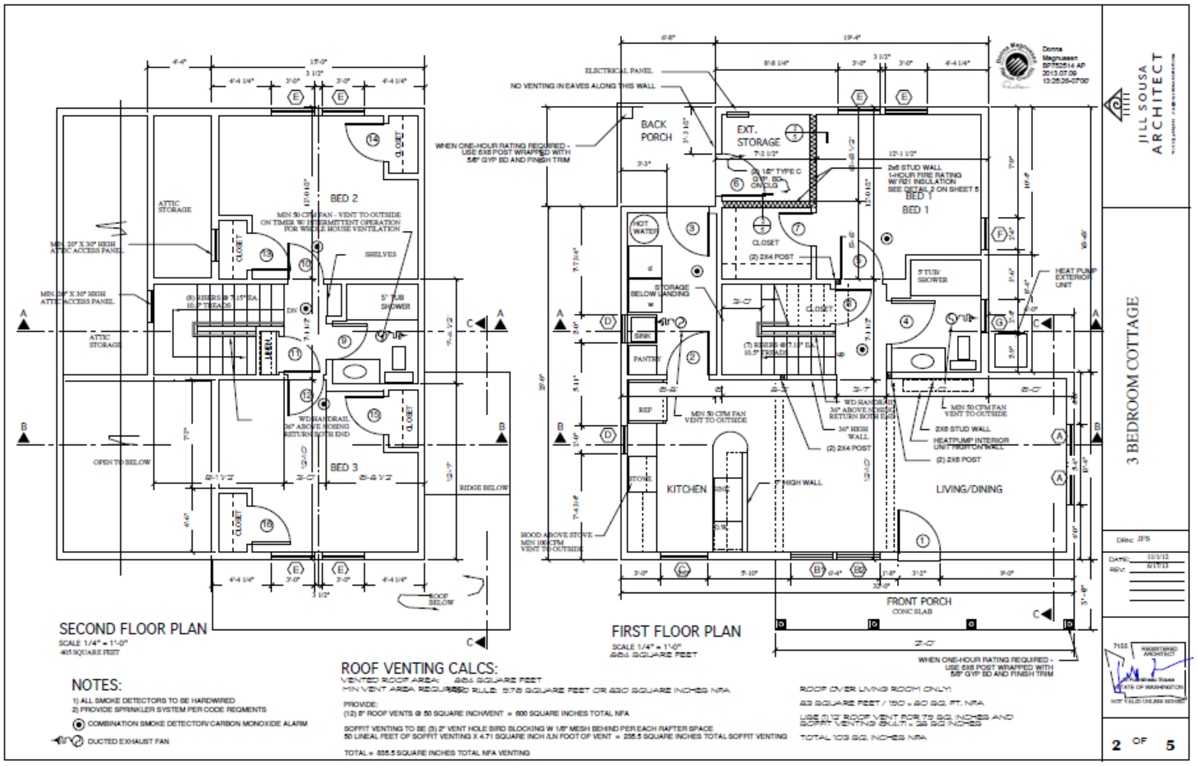
Appendix D: Floor Plans and Sections

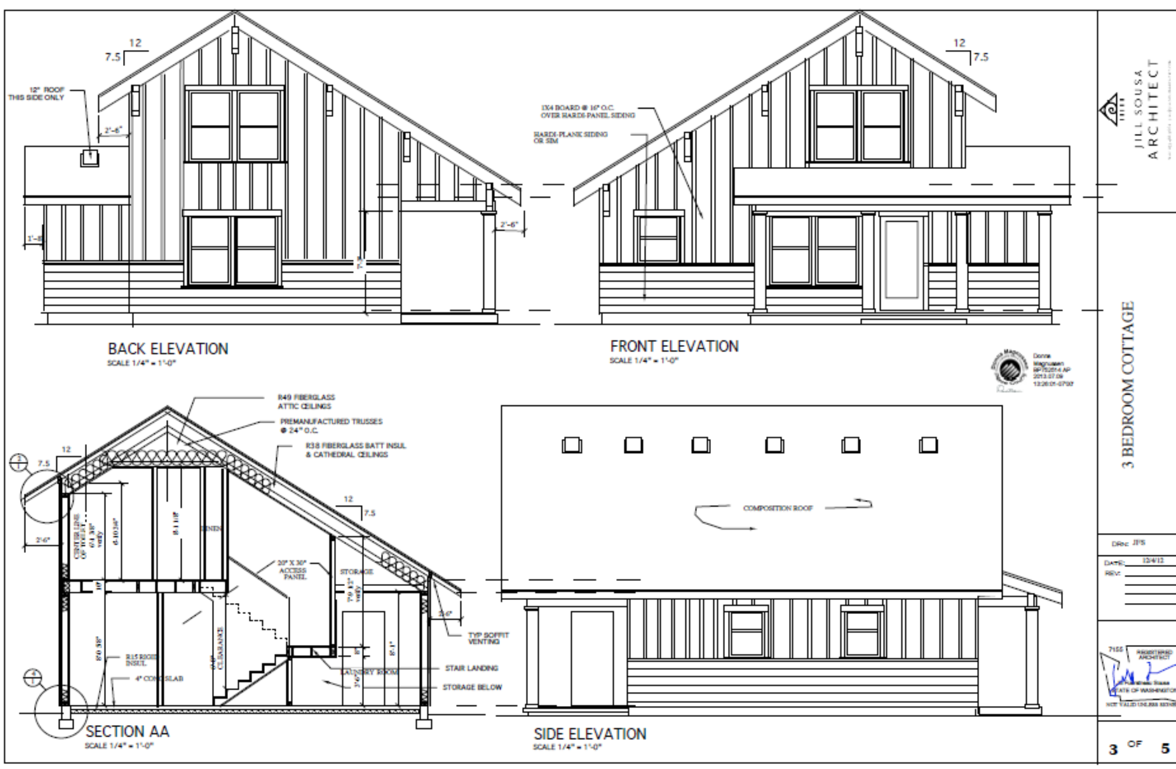
El Jeffe "Pine"



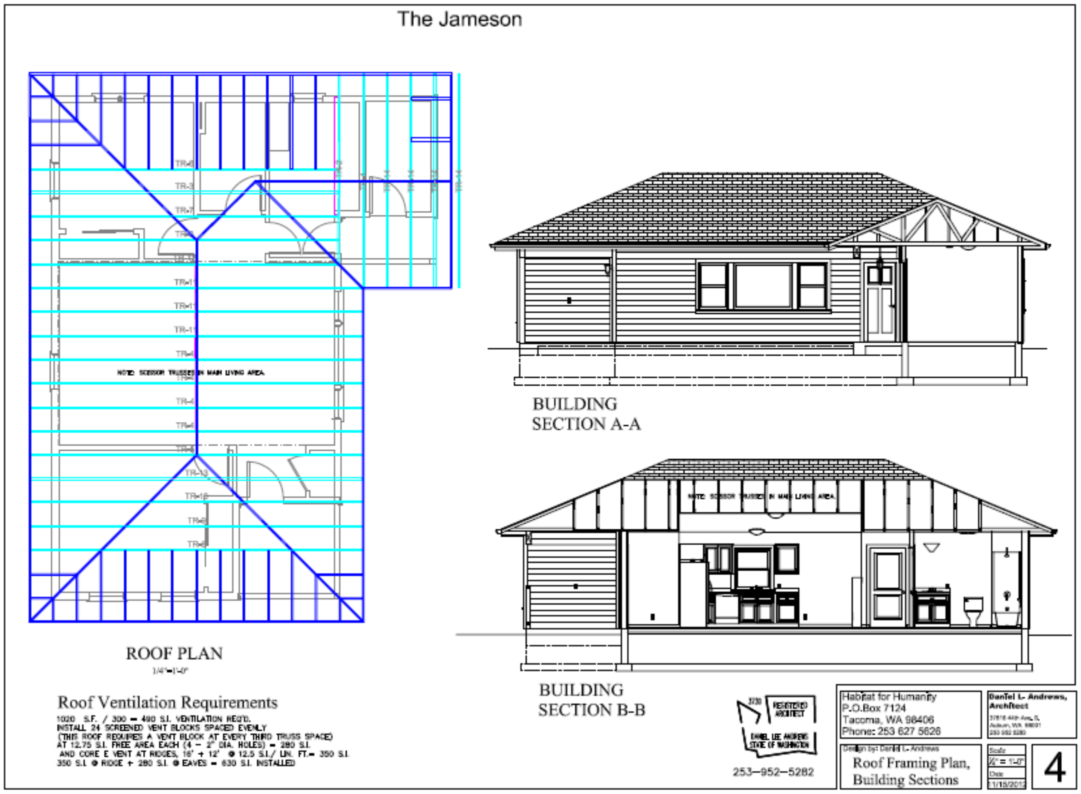


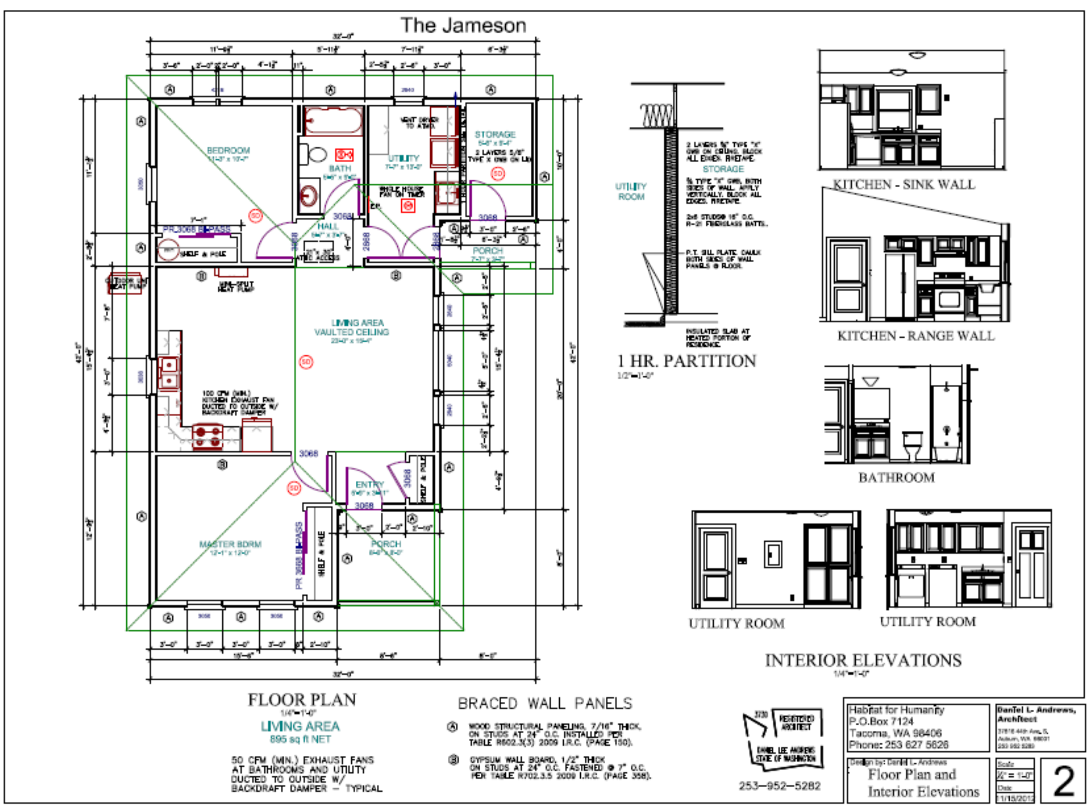
Cottage "Larch"



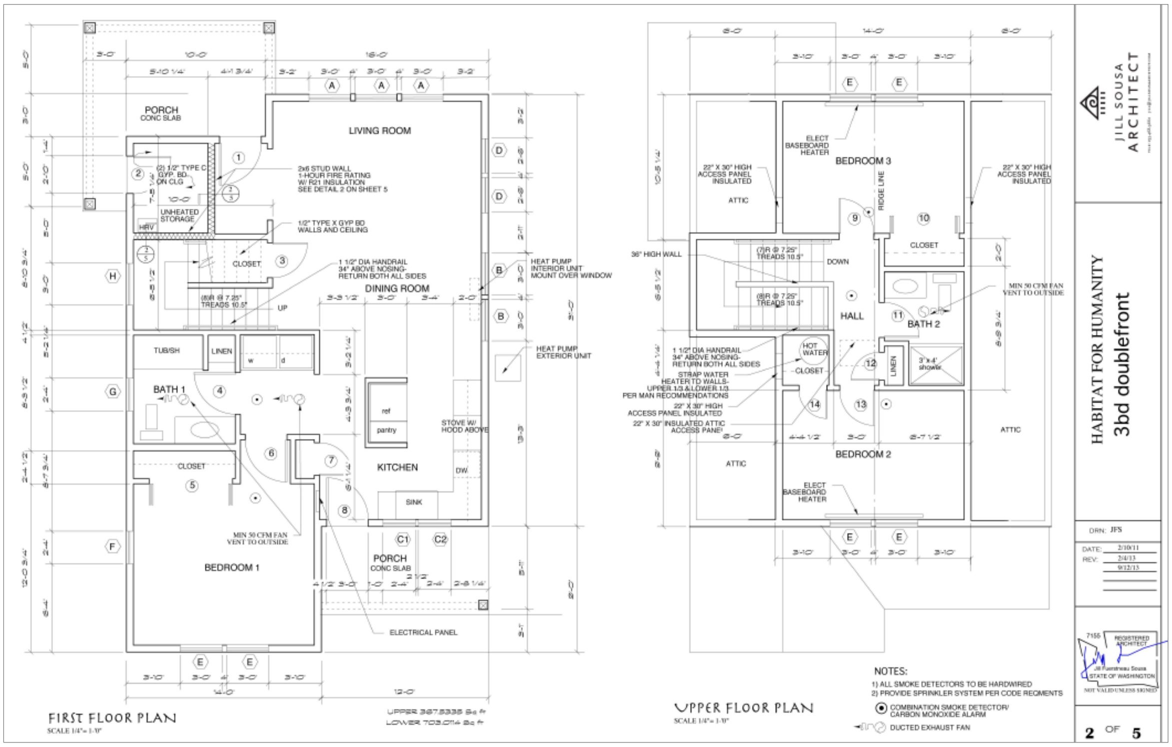


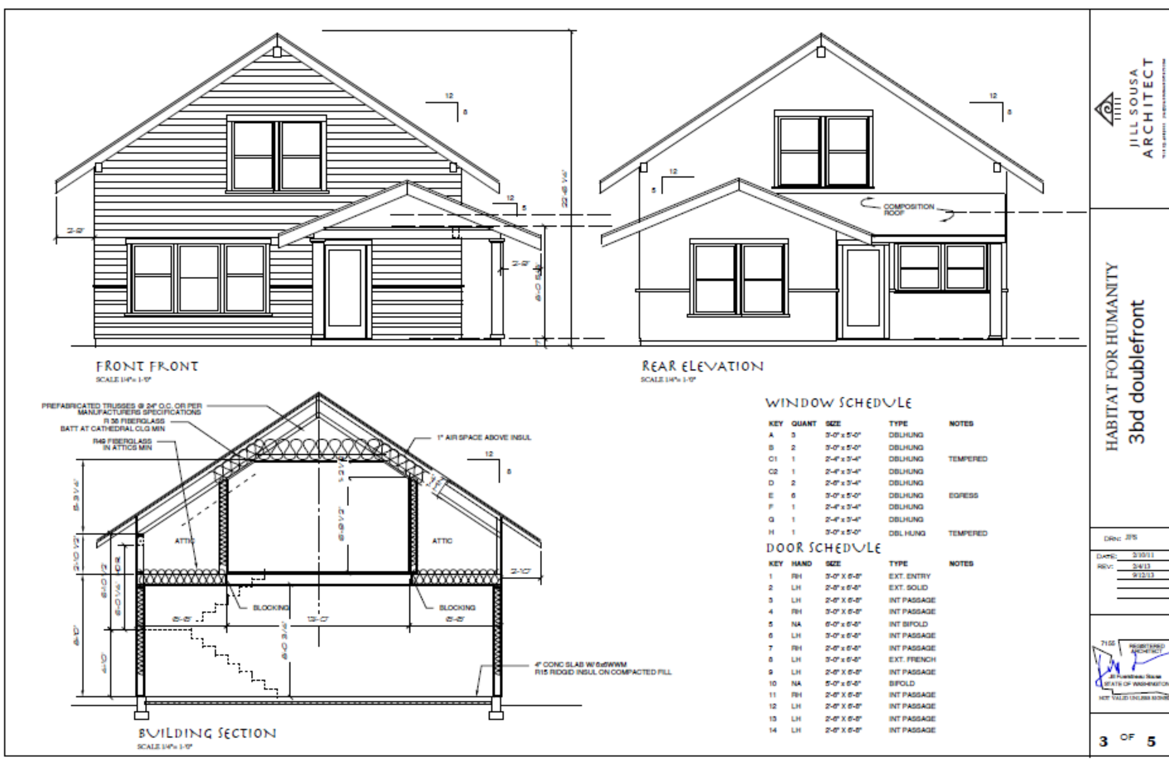
Jameson "Maple"



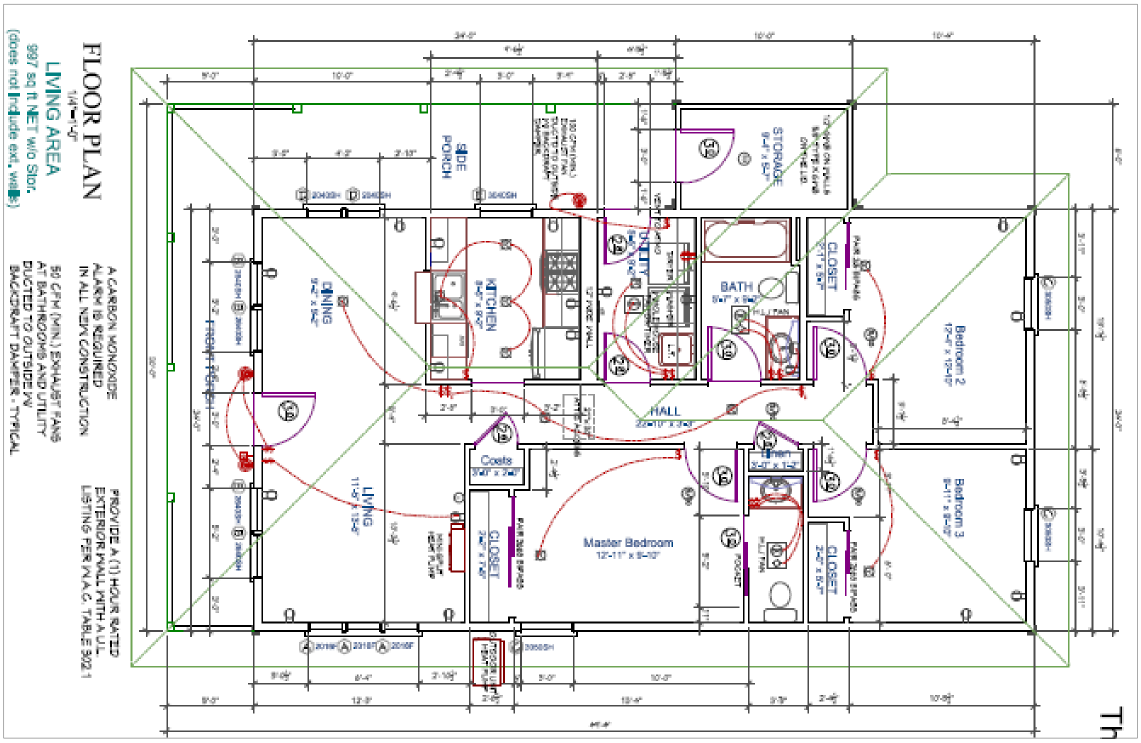


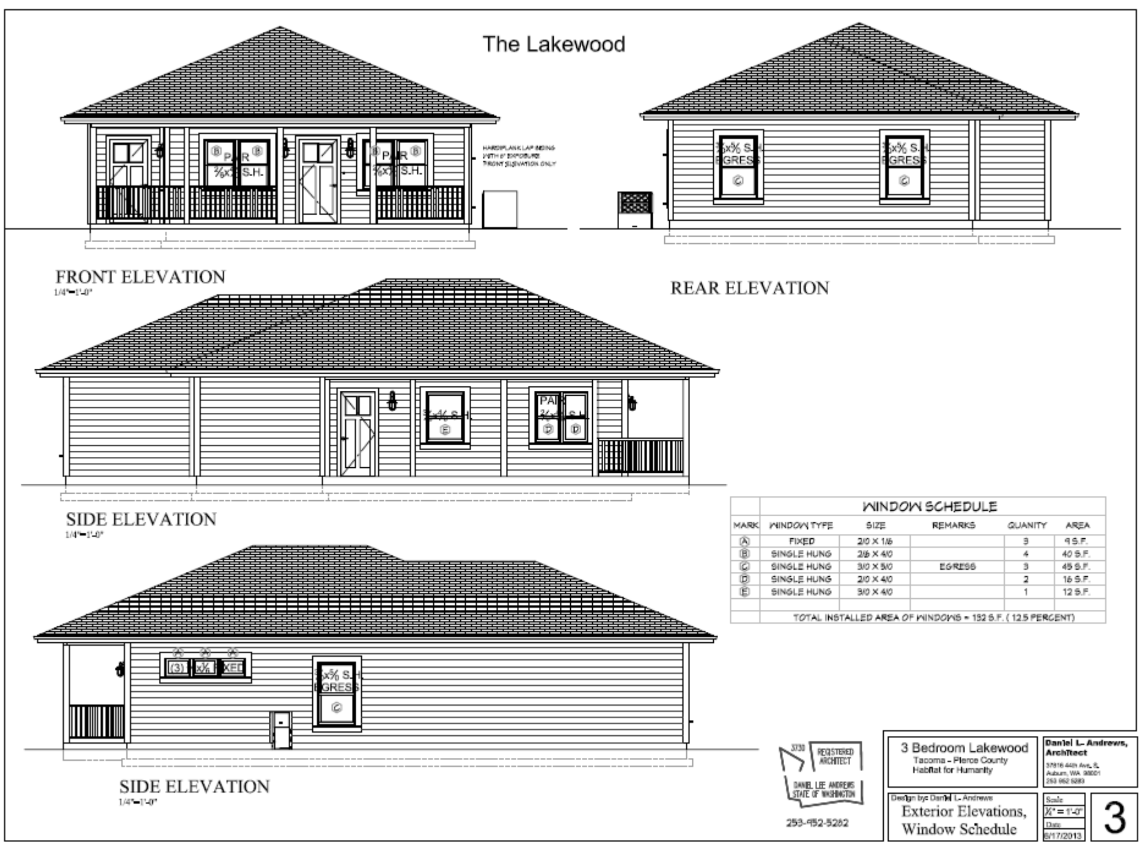
Three-Bedroom Double-Front "Fir"





Lakewood "Oak"





Appendix E: Fire-Suppression Sprinkler System

Insulated box for fire-suppression sprinklers used to help seal and separate from loose fill attic insulation

1/6-in. gap required by manufacturer that cannot be sealed

Sprinkler rough install

Sprinkler insulation freeze-protection tent over pipe

Sprinkler plumbing with tented insulation required by fire marshal

Installed sprinkler housing at dry wall stage prior to indoor head installed

Appendix F: ENERGY STAR Verifier Report and Compliance

The homes at The Woods were constructed and certified to Northwest ENERGY STAR Version 3 standards (Northwest Energy Efficiency Alliance 2013). In September and October 2013, WSU Energy Program staff conducted ENERGY STAR Quality Assurance visits to lots 2, 3, 5 and 6. Under the Northwest ENERGY STAR standards, the verifier (field inspector) is required to conduct full inspections of the home to be certified; these inspections include insulation inspections, blower door testing, duct testing (where appropriate), and fan flow testing of whole-house and local (kitchen and bath) ventilation. Findings from these inspections are reported on checklists that cover thermal enclosure, water management, and HVAC commissioning (Northwest Energy Efficiency Alliance 2013).

According to the HVAC commissioning checklists, all whole-house and local ventilation systems are required to comply with ASHRAE 62.2-2009. During the quality assurance visits, it was determined that the verifier had not completed fan flow commissioning for either the whole-house or local ventilation systems. WSU Energy Program staff worked with the verifier and the performance testing contractor to train them on the proper testing of these systems. This is an ongoing issue with ENERGY STAR quality assurance because builders and inspectors work to bring homes into compliance with the Version 3 specifications. (Version 2, which had no such requirements, sunsetted in June 2012, though some low-income housing entities such as HFH were allowed to continue to use the Version 2 specifications through the end of 2012.)

These ventilation system commissioning issues are exacerbated as balanced ventilation systems, such as those used at The Woods, see broader deployment. Many verifiers do not possess the necessary equipment to test HRVs as well as bath and kitchen ventilation systems. Additional equipment and clear, consistent protocols are necessary to properly measure airflow for kitchen range hoods.

ENERGY STAR quality assurance staff members continue to work with verifiers and raters throughout the region to provide training and technical assistance for the testing of ventilation systems. Furthermore, quality assurance staff members are providing assistance to builders in the design, commissioning, and homeowner education requirements for these systems.

The ENERGY STAR verifier and HVAC installer example checklist is attached.

Example Checklists "Pine"

NORTHWEST ENERGY STAR HOMES

Northwest ENERGY STAR® Homes, Version 3 (Rev. 02) Water Management System Builder Checklist[1,2]

Home Address: 10404 10th Ave. E City: Tacoma State: WA

Inspection Guidelines	Must Correct	Builder Verified	Verifier Verified	N/A
1. Water-Managed Site and Foundation				
1.1 Patio slabs, porch slabs, walks, and driveways sloped ≥ 0.25 in. per ft. away from home to edge of surface or 10 ft., whichever is less.[3]	☐	☒	☒	☐
1.2 Back-fill has been tamped and final grade is sloped ≥ 0.5 in. per ft. away from home for ≥10 ft. See Footnote for alternatives.[3]	☐	☒	☒	☐
1.3 Capillary break beneath all slabs (e.g., slab on grade, basement slab) except crawlspace slabs using either: ≥ 6 mil polyethylene sheeting lapped 6-12 in. or ≥ 1" extruded polystyrene insulation with taped joints.[4]	☐	☒	☒	☐
1.4 Capillary break at all crawlspace floors using ≥ 6 mil polyethylene sheeting, lapped 6-12 in., and installed using one of the following three options:[4]				
1.4.1 Placed beneath a concrete slab; OR,	☐	☐	☐	☒
1.4.2 Lapped up each wall or pier and fastened with furring strips or equivalent; OR,	☐	☐	☐	☒
1.4.3 Secured in the ground at the perimeter using stakes.	☐	☐	☐	☒
1.5 Exterior surface of below-grade walls finished as follows: • For poured concrete, concrete masonry, and insulated concrete forms, finish with damp-proofing coating • For wood framed walls, finish with polyethylene & adhesive or other equivalent waterproofing	☐	☐	☐	☒
1.6 Class 1 vapor retarders not installed on the interior side of air permeable insulation in exterior below-grade walls[5]	☐	☐	☐	☒
1.7 Sump pump covers mechanically attached with full gasket seal or equivalent	☐	☐	☐	☒
1.8 Drain tile installed at the footings of basement and crawlspace walls, with the top of the drain tile pipe below the bottom of the concrete slab or crawlspace floor. Drain tile surrounded with ≥ 6 in. of ½ to ¾ in. washed or clean gravel with gravel layer fully wrapped with fabric cloth. Drain tile level or sloped to discharge to outside grade (daylight) or to a sump pump.[6]	☐	☐	☐	☒
2. Water-Managed Wall Assembly				
2.1 Flashing, or equivalent drainage system, at bottom of exterior walls with cladding. In addition, weep holes included for non-structural masonry cladding and weep screed for stucco cladding.	☐	☒	☒	☐
2.2 Fully sealed continuous drainage plane, or equivalent drainage system, behind exterior cladding that laps over flashing in Item 2.1. Additional bond-break drainage plane layer provided behind all non-structural masonry cladding and stucco cladding[7]	☐	☒	☒	☐
2.3 Window and door openings fully flashed[8]	☐	☒	☒	☐
3. Water-Managed Roof Assembly				
3.1 Step and kick-out flashing at all roof-wall intersections, extending ≥ 4" on wall surface above roof deck and integrated with drainage plane above[9]	☐	☒	☒	☐
3.2 For homes that don't have a slab-on-grade foundation and do have expansive or collapsible soils, gutters & downspouts provided that empty to lateral piping that deposits water on sloping final grade ≥ 5 ft. from foundation or to underground catchment system ≥ 10 ft. from foundation.[10]	☐	☐	☐	☒
3.3 Self-sealing bituminous membrane or equivalent at all valleys & roof deck penetrations	☐	☐	☐	☒
3.4 In 2009 IECC Climate Zones 5 and higher, self-sealing bituminous membrane or equivalent over sheathing at eaves from the edge of the roof line to > 2 ft. up roof deck from the interior plane of the exterior wall.	☐	☐	☐	☒
4. Water-Managed Building Materials				
4.1 Wall-to-wall carpet *not* installed within 2.5 feet of toilets, tubs, and showers	☐	☒	☒	☐
4.2 Cement board or equivalent moisture-resistant backing material installed on all walls behind tub and shower enclosures composed of tile or panel assemblies with caulked joints. Paper-faced backerboard shall not be used[11]	☐	☒	☒	☐
4.3 Building materials with visible signs of water damage or mold *not* installed[12]	☐	☒	☒	☐
4.4 Framing members or insulation products having high moisture content *not* enclosed (e.g., with drywall)[13]	☐	☒	☒	☐

Builder Employee: GUY NIELSEN

Builder Signature: [signature] Date: 7/12/2013

Builder has completed Builder Checklist in its entirety, except for items that are checked in the Verifier Verified column (if any)[x]

Verifier Signature: [signature] Date: 2-15-14

Effective for homes permitted starting 06/15/2013 Revised 04/15/2013 Page 13 of 14

NORTHWEST ENERGY STAR HOMES

Northwest ENERGY STAR® Homes, Version 3 (Rev. 02) Thermal Enclosure System Verifier Checklist

Inspection Guidelines	Must Correct	Builder Verified[1]	Verifier Verified	N/A
4.4.5 Advanced framing, including all of the items below:	☐	☒	☒	☐
4.4.5.a All corners insulated to ≥R-6 at edge[17], AND;	☐	☒	☒	☐
4.4.5.b All headers above windows & doors insulated[18], AND;	☐	☒	☒	☐
4.4.5.c Framing limited at all windows & doors[19], AND;	☐	☒	☒	☐
4.4.5.d All interior / exterior wall intersections insulated to the same R-value as the rest of the exterior wall[20], AND;	☐	☒	☒	☐
4.4.5.e Minimum stud spacing of 19 in. o.c. Alternatively, minimum spacing of 16 in. o.c. is permitted if ≥ R-22 wall cavity insulation is installed.[21]	☐	☒	☒	☐
5. Air Sealing				
5.1 Penetrations to unconditioned space fully sealed with solid blocking or flashing as needed and gaps sealed with caulk or foam				
5.1.1 Duct / flue shaft	☐	☒	☒	☐
5.1.2 Plumbing / piping	☐	☒	☒	☐
5.1.3 Electrical wiring	☐	☒	☒	☐
5.1.4 Bathroom and kitchen exhaust fans	☐	☒	☒	☐
5.1.5 Recessed lighting fixtures adjacent to unconditioned space ICAT labeled and fully gasketed. Also, if in insulated ceiling without attic above, exterior surface of fixture insulated to ≥ R-10 to minimize condensation potential.	☐	☐	☐	☒
5.1.6 Light tubes adjacent to unconditioned space include lens separating unconditioned and conditioned space and are fully gasketed.[22]	☐	☐	☐	☒
5.2 Cracks in the building envelope fully sealed				
5.2.1 All sill plates adjacent to conditioned space sealed to foundation or sub-floor with caulk, foam, or equivalent material. Foam gasket also placed beneath sill plate if resting atop concrete or masonry and adjacent to conditioned space.	☐	☒	☒	☐
5.2.2 At top of walls adjoining unconditioned spaces, continuous top plates or sealed blocking using caulk, foam, or equivalent material	☐	☒	☒	☐
5.2.3 Drywall sealed to top plate at all unconditioned attic / wall interfaces using caulk, foam, drywall adhesive (but not other construction adhesives), or equivalent material. Either apply sealant directly between drywall and top plate or to the seam between the two from the attic above or place foam gasket between drywall and top plate.	☐	☒	☒	☐
5.2.4 Rough openings around windows & exterior doors sealed with caulk or foam	☐	☒	☒	☐
5.2.5 Marriage joints between modular home modules at all exterior boundary conditions fully sealed with gasket and foam	☐	☐	☐	☒
5.2.6 All seams at Structural Insulated Panels (SIPs) foamed and/or taped per manufacturer's instructions	☐	☐	☐	☒
5.2.7 In multi-family buildings, the gap between the drywall shaft wall (i.e. common wall) and the structural framing between units fully sealed at all exterior boundaries	☐	☐	☐	☒
5.2.8 Rim / band joists between conditioned and unconditioned space fully sealed using caulk or foam[7]	☐	☒	☐	☐
5.3 Other Openings				
5.3.1 Doors adjacent to unconditioned space (e.g., attics, garages, basements) or ambient conditions gasketed or made substantially air-tight	☐	☒	☒	☐
5.3.2 Attic access panels and drop-down stairs equipped with a durable ≥R-10 insulated cover that is gasketed (i.e., not caulked) to produce continuous air seal when occupant is not accessing the attic[23]	☐	☒	☒	☐
5.3.3 Whole-house fans equipped with a durable ≥R-10 insulated cover that is either installed on the house side or mechanically operated[23]	☐	☒	☐	☐

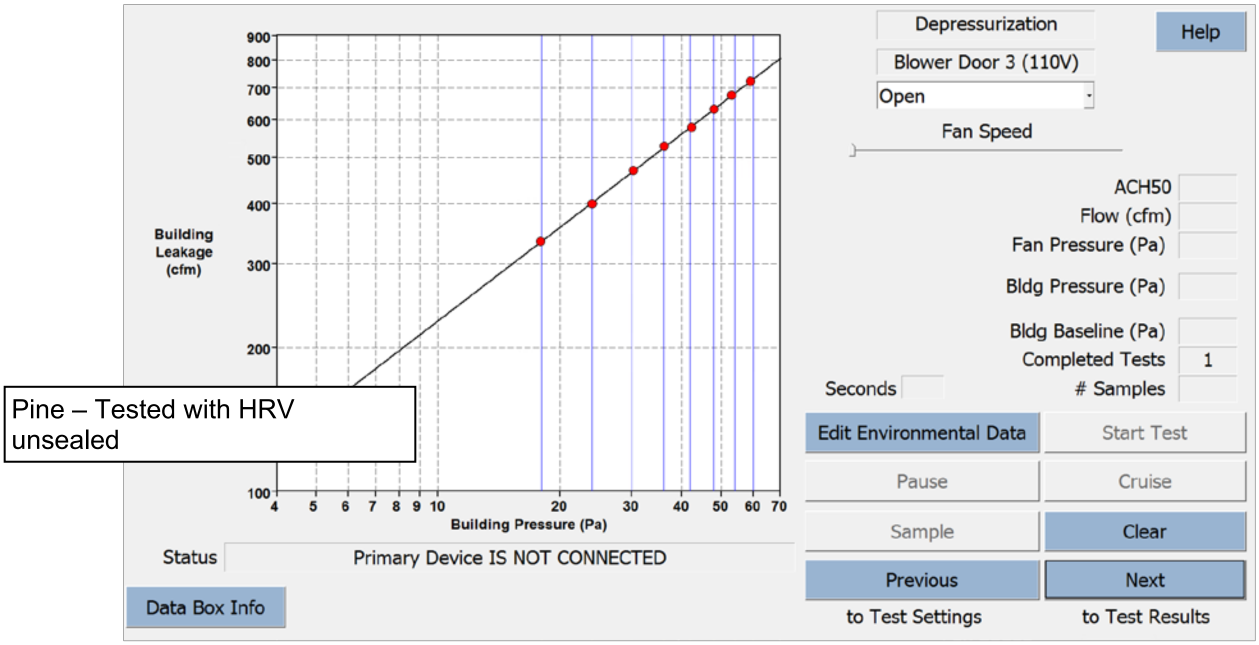
Verifier Name: Diane Glenn   Verifier Pre-Drywall Inspection Date: ✓   Verifier Initials: dg

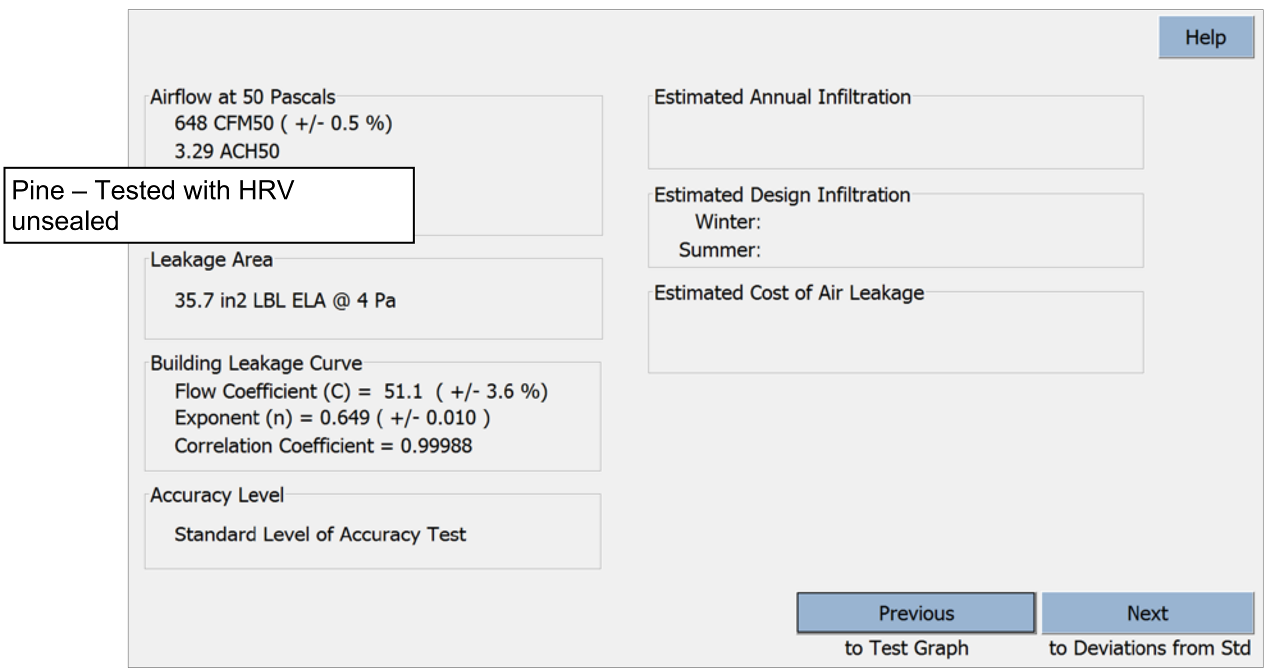
Verifier Name: ____   Verifier Final Inspection Date: 2-15-14   Verifier Initials: dg

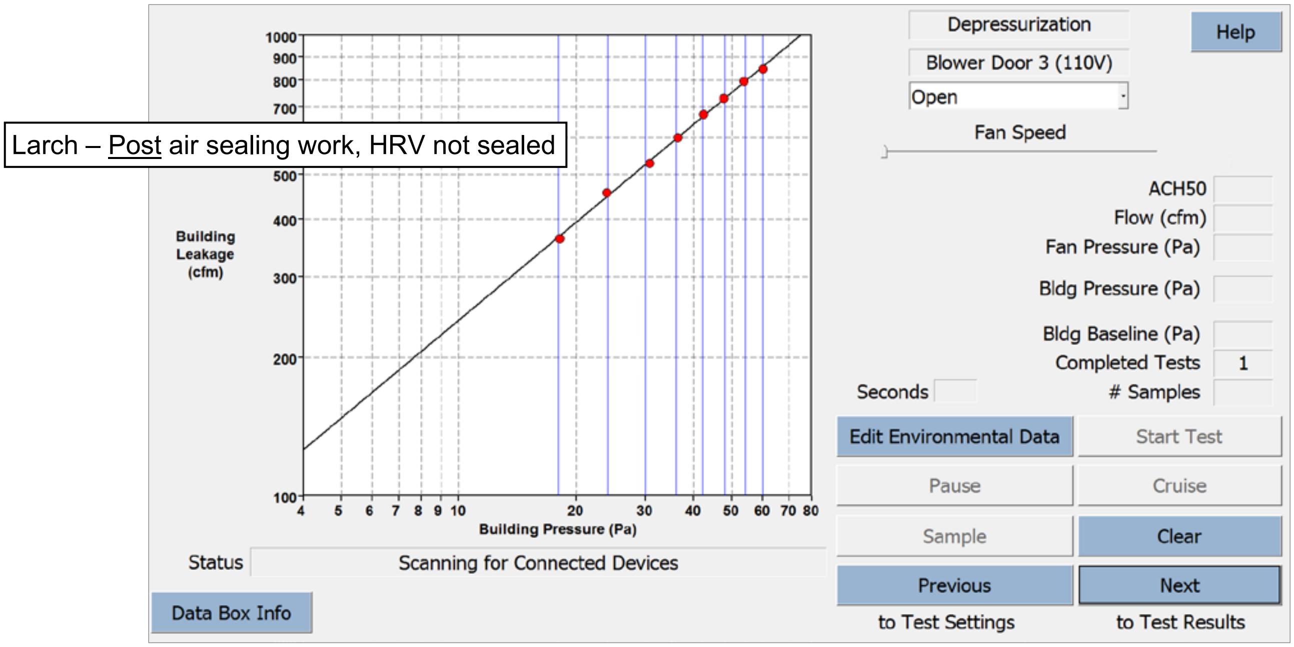
Builder Employee: GUY NIELSEN   Builder Inspection Date: 7/12/2013   Builder Initials: [signature]

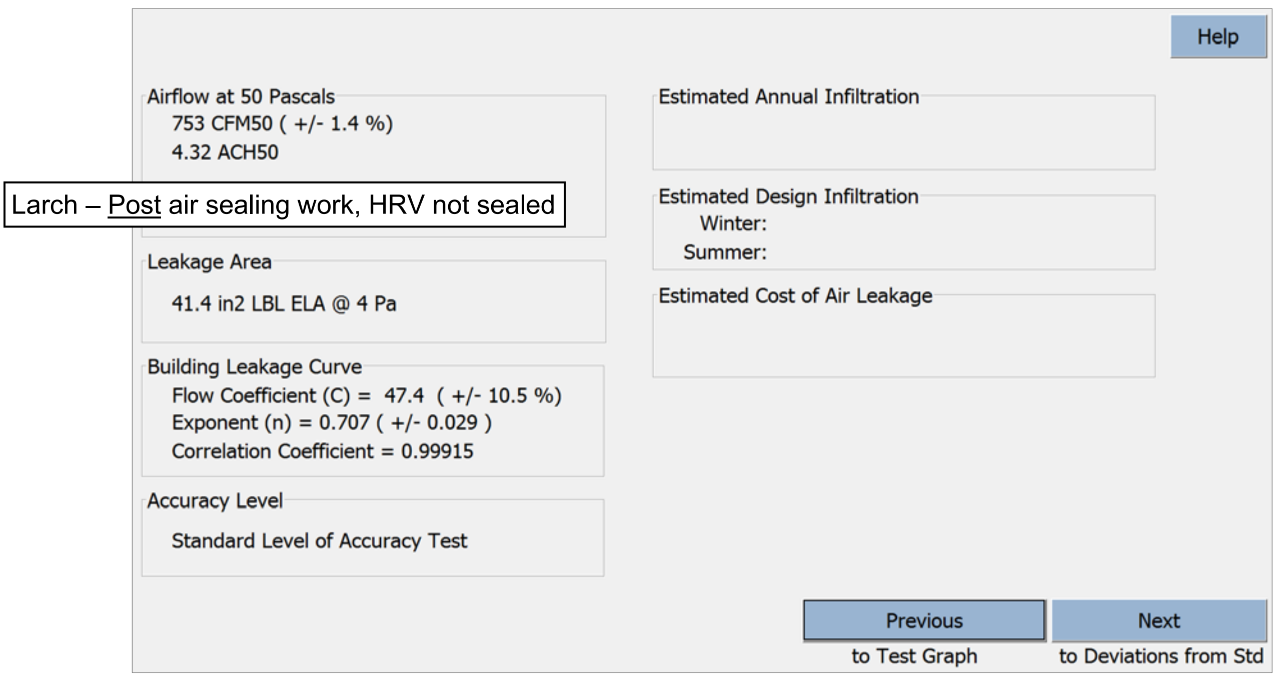
Effective for homes permitted starting 06/15/2013   Revised 04/15/2013   Page 3 of 14

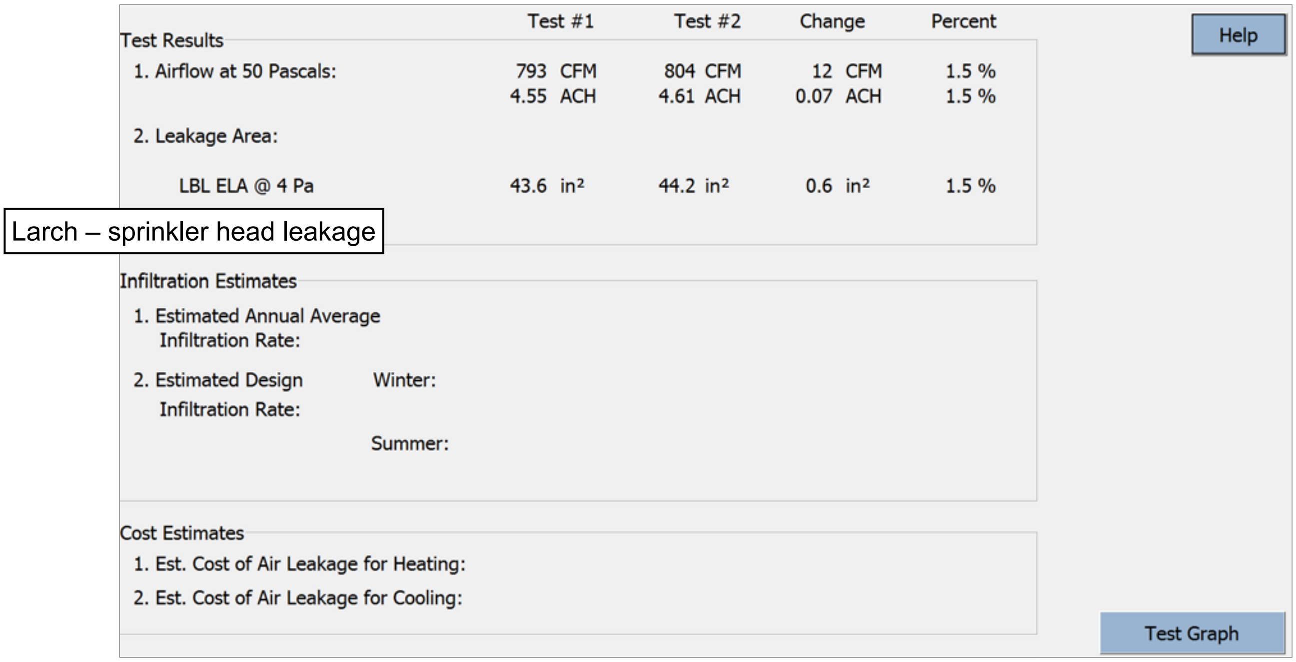
Appendix G: TECTITE Screen Shots

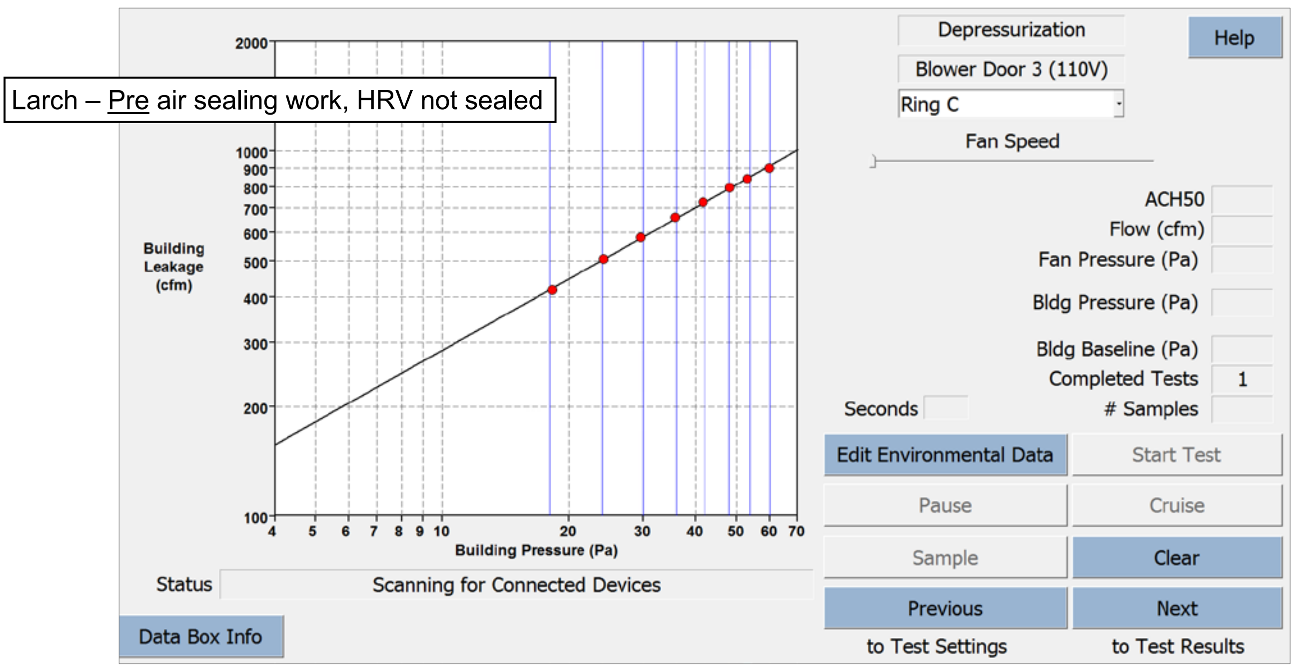


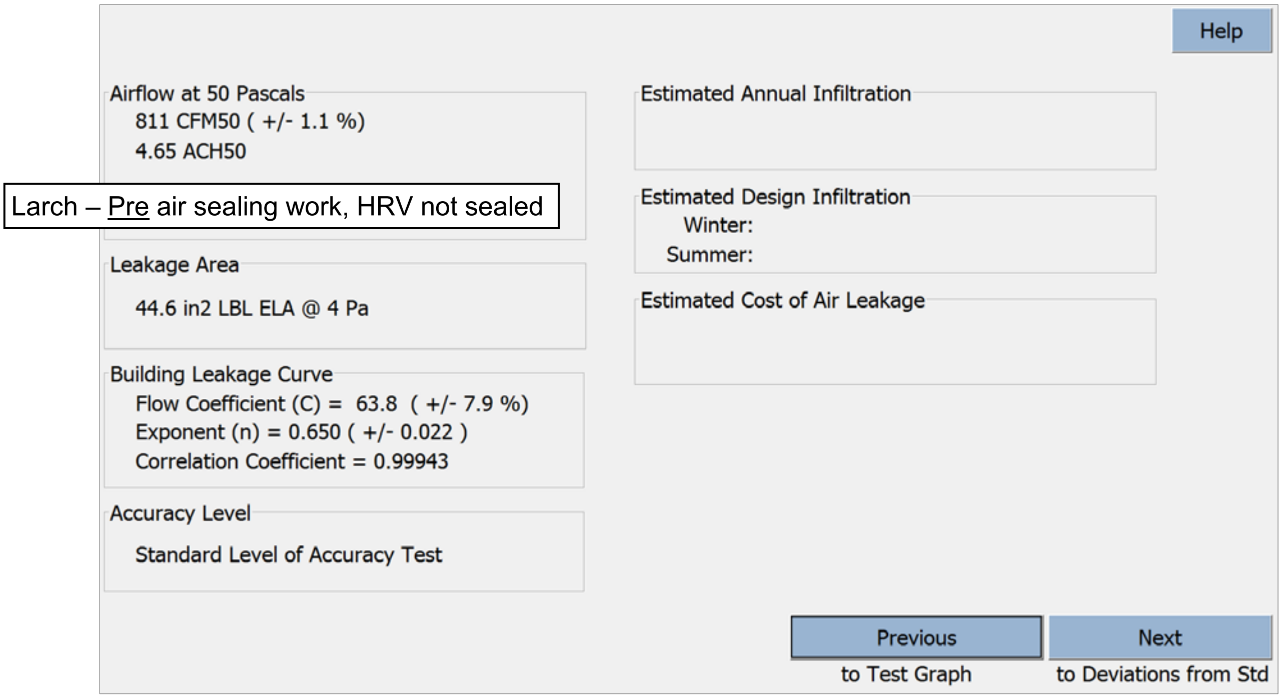


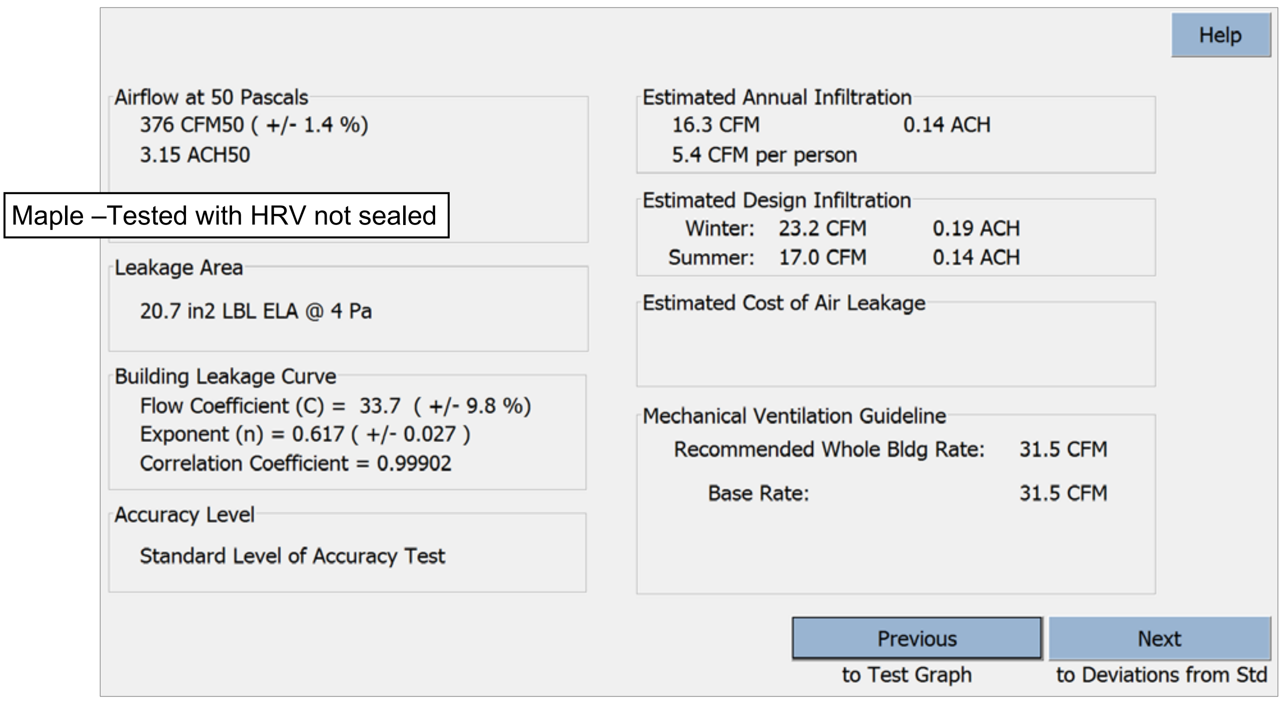

Larch – Post air sealing work, HRV not sealed
Building Leakage (cfm)
Building Pressure (Pa)
Depressurization
Blower Door 3 (110V)
Open
Fan Speed
Help
ACH50
Flow (cfm)
Fan Pressure (Pa)
Bldg Pressure (Pa)
Bldg Baseline (Pa)
Completed Tests 1
Seconds
Samples
Edit Environmental Data
Start Test
Pause
Cruise
Sample
Clear
Status
Scanning for Connected Devices
Previous to Test Settings
Next to Test Results
Data Box Info

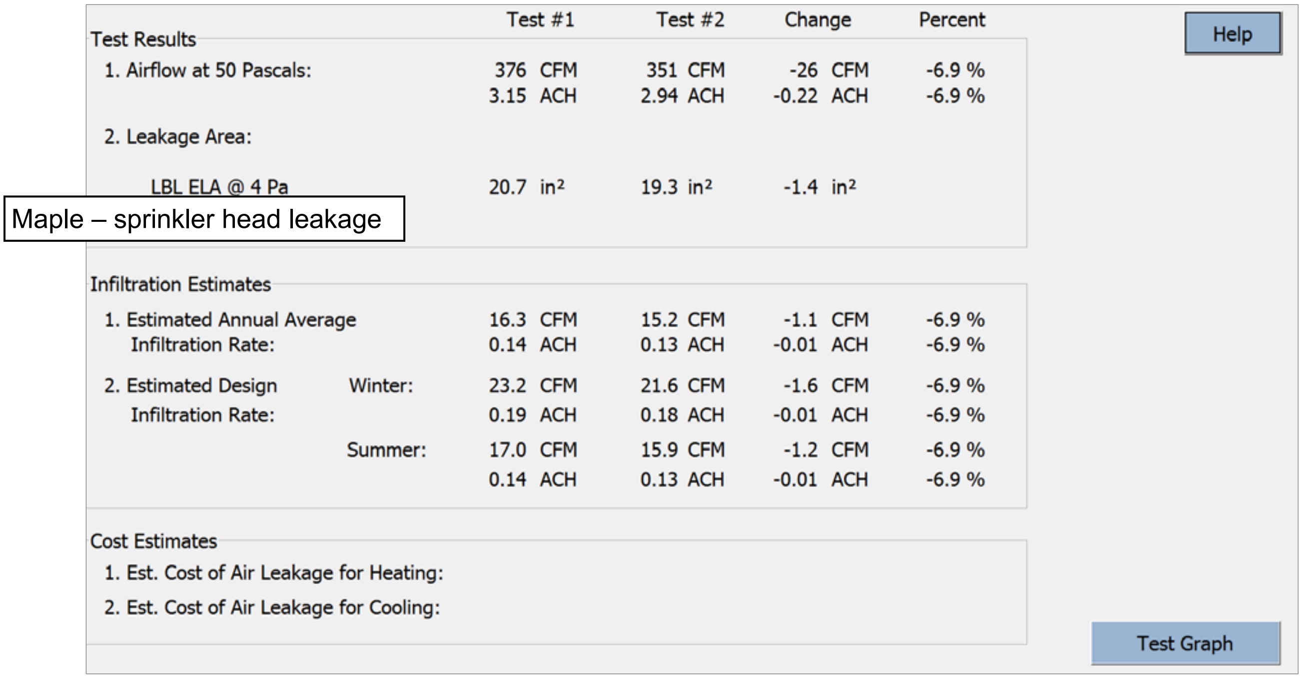

Help
Airflow at 50 Pascals
753 CFM50 (+/- 1.4 %)
4.32 ACH50
Larch – Post air sealing work, HRV not sealed
Leakage Area
41.4 in2 LBL ELA @ 4 Pa
Building Leakage Curve
Flow Coefficient (C) = 47.4 (+/- 10.5 %)
Exponent (n) = 0.707 (+/- 0.029)
Correlation Coefficient = 0.99915
Accuracy Level
Standard Level of Accuracy Test
Estimated Annual Infiltration
Estimated Design Infiltration
Winter:
Summer:
Estimated Cost of Air Leakage
Previous to Test Graph
Next to Deviations from Std


Test #1
Test #2
Change
Percent
Help
Test Results
1. Airflow at 50 Pascals:
793 CFM
804 CFM
12 CFM
1.5 %
4.55 ACH
4.61 ACH
0.07 ACH
1.5 %
2. Leakage Area:
LBL ELA @ 4 Pa
43.6 in²
44.2 in²
0.6 in²
1.5 %
Larch – sprinkler head leakage
Infiltration Estimates
1. Estimated Annual Average
Infiltration Rate:
2. Estimated Design
Infiltration Rate:
Winter:
Summer:
Cost Estimates
1. Est. Cost of Air Leakage for Heating:
2. Est. Cost of Air Leakage for Cooling:
Test Graph


Larch – Pre air sealing work, HRV not sealed
Building Leakage (cfm)
Building Pressure (Pa)
Depressurization
Blower Door 3 (110V)
Ring C
Help
Fan Speed
ACH50
Flow (cfm)
Fan Pressure (Pa)
Bldg Pressure (Pa)
Bldg Baseline (Pa)
Completed Tests
1
Seconds
Samples
Edit Environmental Data
Start Test
Pause
Cruise
Sample
Clear
Previous
Next
to Test Settings
to Test Results
Status
Scanning for Connected Devices
Data Box Info


Help
Airflow at 50 Pascals
811 CFM50 (+/- 1.1 %)
4.65 ACH50
Larch – Pre air sealing work, HRV not sealed
Leakage Area
44.6 in2 LBL ELA @ 4 Pa
Building Leakage Curve
Flow Coefficient (C) = 63.8 (+/- 7.9 %)
Exponent (n) = 0.650 (+/- 0.022)
Correlation Coefficient = 0.99943
Accuracy Level
Standard Level of Accuracy Test
Estimated Annual Infiltration
Estimated Design Infiltration
Winter:
Summer:
Estimated Cost of Air Leakage
Previous
to Test Graph
Next
to Deviations from Std


Help
Airflow at 50 Pascals
376 CFM50 (+/- 1.4 %)
3.15 ACH50
Maple –Tested with HRV not sealed
Leakage Area
20.7 in2 LBL ELA @ 4 Pa
Building Leakage Curve
Flow Coefficient (C) = 33.7 (+/- 9.8 %)
Exponent (n) = 0.617 (+/- 0.027)
Correlation Coefficient = 0.99902
Accuracy Level
Standard Level of Accuracy Test
Estimated Annual Infiltration
16.3 CFM 0.14 ACH
5.4 CFM per person
Estimated Design Infiltration
Winter: 23.2 CFM 0.19 ACH
Summer: 17.0 CFM 0.14 ACH
Estimated Cost of Air Leakage
Mechanical Ventilation Guideline
Recommended Whole Bldg Rate: 31.5 CFM
Base Rate: 31.5 CFM
Previous
to Test Graph
Next
to Deviations from Std

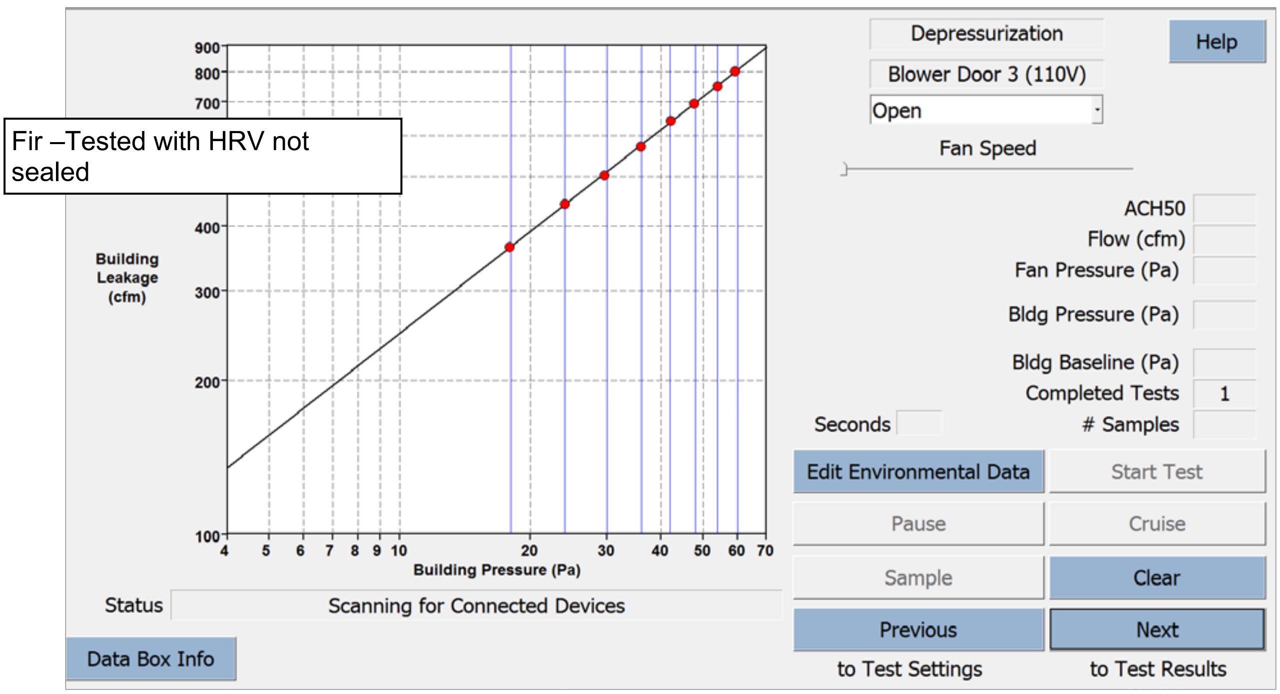


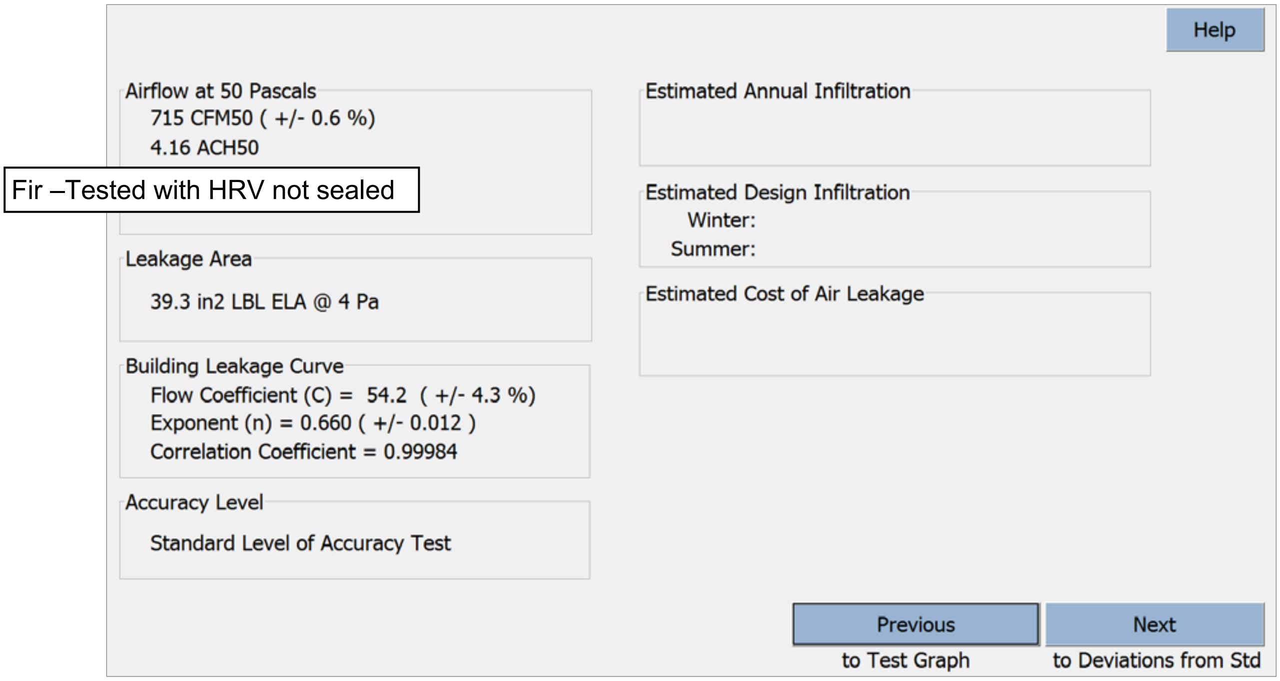
Maple – sprinkler head leakage

Test Results		Test #1	Test #2	Change	Percent
1. Airflow at 50 Pascals:		376 CFM	351 CFM	-26 CFM	-6.9 %
		3.15 ACH	2.94 ACH	-0.22 ACH	-6.9 %
2. Leakage Area:					
LBL ELA @ 4 Pa		20.7 in²	19.3 in²	-1.4 in²	
Infiltration Estimates					
1. Estimated Annual Average Infiltration Rate:		16.3 CFM	15.2 CFM	-1.1 CFM	-6.9 %
		0.14 ACH	0.13 ACH	-0.01 ACH	-6.9 %
2. Estimated Design Infiltration Rate:	Winter:	23.2 CFM	21.6 CFM	-1.6 CFM	-6.9 %
		0.19 ACH	0.18 ACH	-0.01 ACH	-6.9 %
	Summer:	17.0 CFM	15.9 CFM	-1.2 CFM	-6.9 %
		0.14 ACH	0.13 ACH	-0.01 ACH	-6.9 %
Cost Estimates					
1. Est. Cost of Air Leakage for Heating:					
2. Est. Cost of Air Leakage for Cooling:					

Help

Test Graph




Help
Airflow at 50 Pascals
715 CFM50 (+/- 0.6 %)
4.16 ACH50
Fir –Tested with HRV not sealed
Leakage Area
39.3 in2 LBL ELA @ 4 Pa
Building Leakage Curve
Flow Coefficient (C) = 54.2 (+/- 4.3 %)
Exponent (n) = 0.660 (+/- 0.012)
Correlation Coefficient = 0.99984
Accuracy Level
Standard Level of Accuracy Test
Estimated Annual Infiltration
Estimated Design Infiltration
Winter:
Summer:
Estimated Cost of Air Leakage
Previous
to Test Graph
Next
to Deviations from Std

Appendix H: Monitoring Equipment Specifications

1) **ONSET HOBO – U30: Cellular Data Logger – Weekly Download**
   - Normal operating range: –20° to 40°C (–4° to 104°F)
   - Data Channels: Maximum of 15 (some sensors use more than one data channel)
   - Data Storage Memory: Nonvolatile flash data storage, 512 KB local storage
   - Memory Modes: Stop when full, wrap around when full
   - Operational Indicators: Up to seven (depending upon options) status lights provide basic diagnostics
   - Logging Interval: 1 second to 18 hours, user-specified interval
   - Battery Type: 4 volt, 10 AHr Rechargeable sealed lead-acid
   - Rechargeable Battery Service Life: Typical 3–5 years depending upon conditions of use. Operation within the extended operating range (but outside the normal range) will reduce battery service life.
   - Time Accuracy: 0 to 2 seconds for the first data point and ±5 seconds per week at 25°C (77°F)
   - Environmental Rating: Weatherproof enclosure, tested to National Electrical Manufacturers Association 6.
   - Alarm Output Relay: One relay contact closure can be configured as normally open, normally closed, or pulsed. Voltage: t30 V Current: 1 amp max.

2) **ONSET HOBO – UX100-Temp/RH Sensor Data Logger: Temperature (Indoor)**

   - **Range:** -20° to 70°C (-4° to 158°F)
   - **Accuracy:** ±0.21°C from 0° to 50°C (±0.38°F from 32° to 122°F), see Plot A
   - **Resolution:** 0.024°C at 25°C (0.04°F at 77°F); see Plot A
   - **Response Time:** 4 minutes in air moving 1 m/s (2.2 mph)
   - **Drift:** <0.1°C (0.18°F) per year

3) **ONSET HOBO – UX100 Temp/RH Sensor Data Logger Sensor: RH**

   - **Range:** 15% to 95%
   - **Accuracy:** ±3.5% from 25% to 85% over the range of 15° to 45°C (59° to 113°F)
   - **Resolution:** 0.07% at 25°C (77°F) and 30% RH
   - **Response Time:** 43 seconds to 90% in airflow of 1 m/s (2.2 mph)
   - **Drift:** <1% per year typical

4) **ONSET HOBO – Pro v2 Temperature/RH Data Logger**

- Operation range Internal sensors: –40° to 70°C (–40° to 158°F)
- Accuracy: ±0.21°C from 0° to 50°C (±0.38°F from 32° to 122°F)
- Resolution: 0.02°C at 25°C (0.04°F at 77°F)
- Response time (typical to 90%) 40 minutes at 1 m/s Stability (drift): < 0.1°C (0.18°F)/year
- Operation range 0%–100% RH, –40° to 70°C (–40° to 158°F)
- RH may temporarily increase the maximum RH sensor error by an additional 1%
- Accuracy: ±2.5% from 10% to 90% RH (typical), to a maximum of ±3.5% including hysteresis.
- Resolution: 0.03%

5) **ONSET HOBO – S-TNB-M017 – 12 bit temp sensor with 17 meter cable (DHP vapor line)**

- Measurement range: –40° to 100°C (–40° to 212°F) sensor tip*
- Accuracy: < ± 0.2°C from 0° to 50°C (< ±0.36°F from 32° to 122°F)
- Resolution: < ± 0.03°C from 0° to 50°C (< ± 0.054°F from 32° to 122°F)
- Drift: < ± 0.1°C (0.18°F) per year
- Response time:
  < 3 minutes typical to 90% in 1 m/s airflow
  < 30 seconds typical to 90% in stirred water

6) **ONSET T-MAG-SCT-100 – 100 amp split core AC CTs**

- Rated input from 0 Amp to 100 Amp
- Output 0.333 Volt AC at rated current
- Operates from 30 Hz to 1,000 Hz
- Phase angle < 2 degrees measured at 50% rated current
- Linearity accuracy ± 1%
- 8 ft. twisted-pair lead
- Accuracy at 10% to 130% of rated current

7) **ONSET HOBO T-MAG-SCT-50 – 50 amp split core AC CTs**

- Accuracy: ±0.75% from 1% to 120% of rated primary current
- Phase angle: ±0.5 degrees (30 minutes) from 1% to 120% of rated current
- Accuracy standards: IEEE C57.13 class 1.2 and IEC 60044-1 class 1.0

- Primary rating: 5 to 250 Amps, 600 Vac, 60 Hz nominal
- Output: 333.33 mVac at rated current
- Operating temperature: –30° to 55°C (86° to 131°F)

8) WattNode WNB-3Y-208-P – Pulse Input Adapters

- Wye Configuration ranges: Neutral required 1 Phase 3 Wire 120V/240V
- Operating: voltage range: ±20% of nominal
- Frequency: 60 Hz
- CT input: 0–0.5 VAC operating, 3 VAC maximum
- Accuracy: ±0.45% of reading + 0.05% FS through 25th harmonic

9) The Energy Conservatory Flow Blaster

- Flow Range Ring 3 10–120 CFM
- Flow Accuracy: ± –5% of indicated flow or ± 2 CFM, whichever is greater

10) TSI Alnor Jr. Balometer

- Flow Range 10–500 CFM
- Accuracy ±3% + 5 CFM

Appendix I. Multivariable Regression Output

Reference TPU Energy Code Council Report

lm(formula = HVAC_kWh_FT2 ~ HVAC_System_Type + McChord_Temp_Daily + McChord_Temp_DailySQ + Occupants + Num_BdRm + Jan + Feb + Mar + Apr + Jun + Jul + Sep + Oct + Nov + Dec, data = Data set)

Residuals:

Min	1Q	Median	3Q	Max
–0.0223283	-0.0039083	–0.0000588	0.0033016	0.0287907

Coefficients:

	Estimate	Std. Error	t value	Pr(>|t|)
(Intercept)	6.566e-02	2.889e-03	22.725	< 2e-16 ***
HVAC_System_Type	–6.891e-03	2.735e-04	–25.198	< 2e-16 ***
McChord_Temp_Daily	–1.791e-03	1.282e-04	–13.974	< 2e-16 ***
McChord_Temp_DailySQ	1.221e-05	1.454e-06	8.396	< 2e-16 ***
Occupants	1.081e-03	1.942e-04	5.565	2.99e-08 ***
Num_BdRm	–3.968e-04	2.632e-04	–1.508	0.1318
Jan	6.535e-03	7.458e-04	8.762	< 2e-16 ***
Feb	5.700e-03	8.697e-04	6.554	7.21e-11 ***
Mar	3.711e-03	7.644e-04	4.855	1.30e-06 ***
Apr	1.017e-03	7.043e-04	1.444	0.1489
Jun	–2.982e-04	6.742e-04	–0.442	0.6583
Jul	7.583e-04	1.100e-03	0.689	0.4909
Sep	–1.649e-03	8.613e-04	–1.914	0.0557
Oct	8.116e-04	6.253e-04	1.298	0.1945
Nov	4.139e-03	7.186e-04	5.760	9.78e-09 ***
Dec	6.024e-03	7.208e-04	8.357	< 2e-16 ***

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Residual standard error: 0.005946 on 1895 degrees of freedom

Multiple R-squared: **0.714**, Adjusted R-squared: 0.7118

F-statistic: 315.4 on 15 and 1895 DF, p-value: < 2.2e-16 buildingamerica.gov

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

DOE/GO-102016-4774 ▪ February 2016