Evaluation of the New Homes Ductless Heat Pump Pilot

Final Report

April 16, 2019

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1 Executive Summary

Energy Trust's New Homes program launched a Ductless Heat Pump (DHP) Pilot to obtain a better understanding of DHP systems they were seeing come through the program that were combined with ducted air handling systems in newly constructed homes in Oregon. These ducted DHP systems distributed conditioned air using a continuously operating fan. The Program Management Contractor (PMC) monitored the performance of a sample of homes with these types of DHP systems. They tested the feasibility of distribution fan control systems as part of the research, as well. The evaluation approach included background document review, in-depth interviews with New Homes program and PMC staff members, a web survey of pilot home occupants, and comparing billing analysis results to energy modeling outputs to assess how well program energy models estimate energy usage for the different DHP systems.

The DHP systems assessed in the pilot, struggled to produce acceptable levels of thermal comfort for all occupants. Some occupants were satisfied, while others were very dissatisfied. Dissatisfied occupants noted significant temperature differentials across rooms. Furthermore, fan noise created suboptimal overall comfort for some occupants. Temperature monitoring identified variation in temperatures greater than 2°F from room to room for many of the homes, for much of the study period, which suggests the systems are unable to produce even airflow to different rooms in the home. The New Homes program energy models produced fairly good predictions of true energy usage for these homes. The energy models slightly overestimated electricity usage of homes with first generation DHP systems, on average, but underestimated electricity usage of homes with second generation systems. Adding controls to the air distribution fans, so that they do not continuously operate, may save significant energy, although the pilot was unable to quantify this value.

The pilot was unable to assess how the energy performance of the ducted DHP homes compares to homes with a ducted heat pump or more typical DHP systems.

The typical material costs for DHP systems for a 2,000 square foot house were around $2,000 to $2,700. Installation labor costs added between $1,100 and $1,500, but the cost to install the systems was highly dependent on the layout and size of the home. These systems have additional equipment and labor costs compared to typical DHP systems, related to the addition of ducting and fans. The ducted DHP systems are still less expensive than installing a central ducted system. Adding fan controls to these systems would cost approximately $200 for materials and roughly $500 in labor.

MEMO

Date: March 21, 2019
To: Board of Directors
From: Scott Leonard, Sr. Project Manager, Residential Sector
Mark Wyman, Sr. Program Manager, Residential Sector
Dan Rubado, Evaluation Project Manager
Subject: Staff Response to the New Homes DHP Pilot Evaluation

The evaluation of the New Homes program's Ductless Heat Pump (DHP) pilot completed by Evergreen Economics showed the concepts of ducted DHPs and homes conditioned only with DHPs are still in development and rapidly evolving. The version of the DHP and ducting equipment configuration that we evaluated appeared to be quite energy efficient and performed roughly as modeled on average, but there were several major issues with these systems. They struggled to produce uniform temperatures and acceptable levels of comfort in homes. Homeowners had relatively low satisfaction with these systems and complained about comfort and noise. In addition, the air distribution systems were somewhat inefficient—a significant and relatively simple opportunity to further reduce energy consumption.

Energy Trust will not recommend the configuration of DHP equipment tested and evaluated in this pilot to program builders or verifiers. In addition, the program modeling protocols were recently updated to more accurately estimate energy usage and savings from various DHP system configurations, including those with ducts. The configuration of equipment tested in this pilot will generally not qualify for incentives because the energy models now show insufficient savings. There is a new type of DHP system that is manufactured with an integrated air handler and duct system. In theory, this should be a more functional and efficient solution. The modeling protocol updates also cover this equipment configuration and initial tests show it will generally produce significant savings and qualify for incentives. The program will not pursue a pilot of the new system type but does plan to conduct additional quality assurance site visits to ensure that proper installation, ducting and temperature distribution are achieved.

2 Introduction and Study Objectives

Energy Trust of Oregon engaged Evergreen Economics in October 2017 to conduct an evaluation of Energy Trust of Oregon's New Homes Ductless Heat Pump (DHP) Pilot. The New Homes program launched the DHP Pilot to obtain a better understanding of DHP systems they were seeing come through the program that were combined with ducted air handling systems in newly constructed homes in Oregon.

The first iteration of the ducted DHP system included a standard DHP indoor unit on the first floor along with a second indoor unit in a hallway on the second floor that served multiple rooms via a ducting system. Air was distributed through the ducting with a bathroom fan. This approach—version 1 (V1)—was updated to version 2 (V2) to better and more equally serve the rooms on the second floors. The V2 DHP system incorporates larger distribution fans in the ductwork on the second floor unit, and the second floor unit is installed in a hallway or closet with a return air vent. The purpose for both the V1 and V2 DHP systems is to deliver energy efficient heating and cooling at a lower cost than standard central ducted heat pump to systems.

The DHP Pilot included a field monitoring research component. The DHP Pilot's Program Management Contractor (PMC), CLEAResult, monitored the performance of a sample of homes with V2 DHP systems. They tested the feasibility of distribution fan control systems as part of the research, as well.

This evaluation covers primary and secondary research questions identified by Energy Trust. The primary research questions of the DHP Pilot directly addressed in this evaluation include:

- How well do the program energy models estimate the actual heating energy usage and energy savings for these types of DHP systems?
- Can these systems produce acceptable levels of thermal comfort for occupants?

Secondary research questions addressed in this report include:

- What are the equipment and installation costs of these systems?
- How do these systems compare with more typical DHP systems and central ducted systems in terms of energy use and cost?
- What equipment or installation procedures will allow reliable control of the distribution system with a low incremental cost?
- What is the difference in energy consumption for the systems with continuously versus intermittently operating air distribution systems?

Additional primary and secondary research questions addressed by the PMC, and reviewed by this evaluation include:

- Can these systems produce sufficient airflow and relatively even air temperatures throughout different rooms in the home?
- Can intermittent air distribution produce sufficient airflow and relatively even air temperatures throughout different rooms in the home? How does it compare with continuous operation?
- How much time does the DHP system operate throughout the year?
- How many CFM do the distribution systems deliver to each room, on average?
- How much does it cost to add air distribution controls to these systems?

The evaluation approach included background document review, in-depth interviews with New Homes program and PMC staff members, a web survey of pilot home occupants, and comparing billing analysis results to energy modeling outputs to assess how well program energy models estimate energy usage for the different DHP systems.

3 Research Methods

This section presents the methods used for this evaluation. The research activities are broken into background and primary research.

3.1 Background Research

Background research included a review of pilot documents, data, and analysis methods.

3.1.1 Pilot Document Review

The Energy Trust Evaluation Project Manager provided Evergreen Economics with a number of background documents related to the DHP Pilot. These include:

- **Business Brief:** an internal Energy Trust of Oregon document making the business case for the DHP Pilot. This document provides an overview of how the pilot fits into Energy Trust's portfolio of energy efficiency and emerging technologies initiatives and documents numerous research questions.
- **Implementation Plan:** the plan for implementing the DHP Pilot, produced by the PMC for Energy Trust. This document provides a background section including the goals of the DHP Pilot and the research questions it intends to answer. The document also lays out the design of the study at a high level (e.g., recruitment and incentive strategy, sampling approach), as well as introduces the subsequent evaluation framework.
- **Monitoring Plan:** the detailed monitoring instrumentation plan contains information regarding the data collection strategy and specific procedures for equipment installation, as well as specifying the proposed equipment to be used for the monitoring study. It also provides a schedule and list of consent and data collection forms.
- **Recruitment Letter:** a one-page letter to prospective participant homeowners that provides details of the study and incentive, as well as contact information for the DHP Pilot implementation team.
- **Recruitment Flyer:** a double-sided customer-facing recruitment flyer, which contains details about the study and incentive, as well as contact information for the DHP Pilot program.
- **Web Page (Microsoft Word document):** the copy included on the DHP Pilot website, which is designed for prospective participants to learn more about the study than what they could learn from the initial recruitment letter. The web page content includes bulleted lists of study specifics, as well as an FAQ (frequently asked questions) section.
- **Energy Performance Score (EPS) Incentive Overview Flyer:** a customer-facing double-sided flyer regarding the incentive structure of the EPS Program. The flyer

provides a table of example above code improvement options and potential resulting incentives. It also provides a list of requirements for incentives and a four-step guide for participation.

- **EPS Modeling Reference Guide:** a detailed 20-page document that includes specifics of the REM/Rate modeling approach, used to produce the engineering estimates we compare to our billing analysis results. This document was produced by Energy Trust of Oregon and essentially consists of a guide to building modeling using the REM/Rate software.
- **New Homes Program Implementation Manual (PIM):** a document that outlines the purpose, structure, program offerings (including detailed incentive schedules), an overview of modeling guidelines and calculations, detailed quality assurance procedures, detailed incentive processing processes, new measure development processes, guidelines for engaging both the supply and demand sides of the market, program marketing guidelines, data management procedures, a pilot program process overview, and information specific to the New Homes Program's solar photovoltaic program offering. This is a 156-page document to be used internally by New Homes Program staff members.

The purpose of this review was to familiarize the evaluation team with the DHP Pilot activities and approaches to inform subsequent research tasks. The content of the background documents (i.e., business brief, implementation plans) informed our data collection approaches and research tools. The monitoring plan and EPS modeling guide informed our billing analysis approaches.

3.1.2 Pilot Data and Analysis Review

The Energy Trust Evaluation Project Manager provided DHP Pilot monitoring data following the conclusion of the pilot implementation and data logger removal. The data include temperatures by room, airflow measurements, fan hours of operation, and cost data. Due to an issue with data collection, the data do not include indoor DHP unit runtime.

Evergreen also reviewed the DHP Pilot analysis methods and results, with a focus on identifying data collection issues, methodological problems, or calculation errors.

3.2 Primary Research

The primary research included installation contractor and builder interviews, interviews with DHP Pilot staff members (including employees of both Energy Trust of Oregon and CLEAResult, the DHP Pilot implementer), and an occupant web survey.

3.2.1 Installer Interviews and Site Visit

Evergreen interviewed a representative from the fan control installer firm (an electrical contractor) and a representative from a firm that installed V1 and V2 DHP systems in pilot study homes. An Evergreen staff member also attended an installation of the fan controls and discussed the installation process with the homeowner and installer.

The interviews focused on experiences with the V2 DHP systems installed through the pilot. Specifically, the interviews were designed to inform the following:

- Motivations for installing V2 DHP systems;
- Concerns about the technology;
- Lessons learned from design and installation;
- Barriers to expanding the use of V2 DHP systems; and
- Typical equipment and labor costs.

3.2.2 Staff Interviews

Evergreen interviewed three Energy Trust of Oregon staff members and three CLEAResult staff members. The interviews covered the following topics:

- Pilot design and implementation;
- Data collection and analysis methods;
- Interpretation of findings; and
- Successes, challenges, lessons learned, and future plans as a result of the pilot.

The interviews occurred in October 2018.

3.2.3 Occupant Surveys

Evergreen developed an occupant web survey to address a number of key research goals. This report documents survey findings related to the following topics:

- Motivations for purchasing the home;
- Comfort of the respondent's home;
- Use of HVAC controls and set points; and
- Satisfaction with the system.

We recruited occupants via an introductory letter with a web link and description of the study, as well as information regarding an incentive: a drawing of several prizes (three prizes valued at approximately $200 each). The link directed the occupant to the Qualtrics web survey.

The DHP Pilot's New Homes Program tracking data contains street addresses, but does not contain phone numbers, or email addresses. The data did contain occupant names for homes with V2 DHP systems and some homes with V1 DHP systems, but no names for occupants of non-DHP homes. This led to a lower than planned response rate and an inability to follow-up with occupants via multiple recruitment methods. The numbers of completed surveys with occupants of pilot homes with V1 and V2 DHP systems, as well as occupants of non-DHP homes (with natural gas heat), are shown in Table 1. The number of web survey invite letters sent to occupants are also shown.

Table 1: Occupant Survey Completes

Respondent Group	Number of Completed Surveys	Number of Invite Letters Sent
Occupants of V2 DHP Pilot Homes	4	130
Occupants of V1 DHP Pilot Homes	15	300
Occupants of Non-DHP Homes	5	300

The survey time period ended in December 2018. Evergreen exported the data for analysis and due to the low number of responses, conducted a more qualitative assessment of the DHP Pilot than originally anticipated. We provide the counts of each response, as well as means for scaled questions (i.e., satisfaction ratings). It is not possible to derive statistical significance from the findings.

3.2.4 Billing Analysis

For this task, we used billing analysis to estimate weather normalized energy usage for three distinct DHP system designs installed in homes participating in the New Homes program. These three designs offer different strategies for air distribution on the second floor:

- Version 1 (V1): one bathroom-style fan.
- Version 2 (V2): two 98W high airflow fans, continuous operation.
- Retrofitted version 2 (Retrofitted V2): two 98W high airflow fans with controls, giving occupants the option to operate fans only when DHP is running.

The analysis compares the program's REM/Rate energy usage models to occupants' actual energy usage to assess the accuracy of the models. While the current models indicate that all three system designs produce cost-effective energy savings, relative to the baseline of a central ducted heat pump, the modeled estimates have not been verified. Separate analysis tasks provide estimates of the cost, performance (i.e., ability to provide conditioned air throughout the home), and occupant satisfaction with these systems.

Data Preparation

The sample provided by Energy Trust is shown in Table 2, including monthly billing data from electric and gas utility providers spanning at least one full year after occupancy. The identification of homes with V1 versus V2 DHP systems proved to be more difficult than Energy Trust had originally expected. Builders provided a complete list of homes with DHPs with air distribution systems (regardless of type), and then relied on the contractors to identify homes they had worked on to install V2 DHP systems, assuming that the remainders are homes with V1 systems. Hence, it is possible that some of the DHP homes are misclassified. Four of the homes with V2 DHP systems received a fan controls retrofit in April 2018.[1] We also received a sample of homes from the same builder, time period, and region with non-DHP systems, usually gas furnaces, to act as a comparison group. While we would prefer to compare these DHP systems to a ducted heat pump system, the sample size of comparable homes was insufficient unless we included homes with gas furnaces.

Table 2: Billing Analysis Sample

System Type	Number of Homes Identified	Number with Electric Billing	Number with Gas Billing
V1 DHP	608	434	379
V2 DHP	130	119	119
Retrofitted V2 DHP	4	4	4
Non-DHP (Baseline)	844	650	641

Energy Trust also provided program participation records, Energy Performance Scores (EPS), and REM/Rate modeled energy usage estimates (kWh and therms) for each home.

Regression

The NREL Uniform Methods Project supports the use of either a pooled fixed effects or a variable base degree-day modeling approach for estimating savings from monthly whole-building energy usage data. We have experience with both approaches and believe a fixed effects model balances the need for accuracy, transparency, and ease of interpretation. We used the following fixed-effects regression model specification in our analysis, shown in

[1] These retrofitted homes were a subset of the 19 homes recruited for indoor temperature metering.

Equation 1. A similar model was estimated for therms among homes with gas usage, omitting the cooling terms.

Equation 1: Electric Fixed Effects Regression Model

$$kWh_{i,t} = \alpha_i + \beta_{CDD} CDD_t + \beta_{HDD} HDD_t + \sum_{m=1}^{11} \beta_m Month_t + \sum_{sc=1}^{3} \beta_{sc} (CDD * System)_{i,t} + \sum_{sh=1}^{3} \beta_{sh} (HDD * System)_{i,t} + \varepsilon_{it}$$

Where :

$$\begin{aligned}
kWh_{i,t} &= \text{Electricity usage per day, during month } t \text{ for home } i \\
\alpha_i &= \text{Baseload usage estimate (i.e., fixed effect), for home } i \\
CDD_t, HDD_t &= \text{Cooling and heating degree-days, during month } t \\
System_{i,t} &= \text{Set of binary variables indicating which air distribution} \\
&\quad \text{system home } i \text{ has in month } t \\
CDD * System &= \text{Interaction between cooling degree-days and the system type} \\
Month_t &= \text{Set of binary variables indicating whether billing month } t \text{ is in} \\
&\quad \text{January, March, February,...} \\
\beta &= \text{Model coefficients, determined by the regression} \\
\varepsilon &= \text{Regression residual, assumed to be normally distributed}
\end{aligned}$$

Next, we used the coefficients estimated by the regression model to calculate each home's weather-normalized energy usage, based on the average daily cooling degree-days (CDD) and heating degree-days (HDD) during the typical meteorological weather-year (TMY3) as shown in Equation 2. This process normalizes each home's energy usage to reflect the same weather conditions that were used by the REM/Rate model.

Equation 2: Estimate of Normalized Daily Electricity Usage

$$NormkWh_i = \hat{\alpha}_i + \hat{\beta}_{CDD}\overline{CDD_{TMY}} + \hat{\beta}_{HDD}\overline{HDD_{TMY}} + \frac{\sum_{m=1}^{11}\beta_m Month_t}{12} + \sum_{sc=1}^{3}\hat{\beta}_{sc}(\overline{CDD_{TMY}} * System_i) + \sum_{sh=1}^{3}\hat{\beta}_{sh}(\overline{HDD_{TMY}} * System_i)$$

Where :

$NormkWh_{i,t}$ = Normalized daily electricity usage estimate, for home i

$\hat{\alpha}, \hat{\beta}$ = Model coefficients estimated in the previous regression

$\overline{CDD_{TMY}}, \overline{HDD_{TMY}}$ = Average daily cooling and heating degree-days, for home i during the typical meterological year

Comparing the weather-normalized energy usage estimates from the regression analysis for pilot homes with V1 and V2 DHP systems that share similar characteristics (e.g., square-footage, building year, number of floors) will provide an estimate for the relative energy usage attributable to each DHP air distribution system. In addition, the coefficients on the air distribution system and interaction variables will provide insights into the weather conditions when differences were observed for each of the three system designs, relative to each other.

Our next task was to compare this normalized annual estimate of energy usage (kWh and therms) to the program models' predicted usage for V1 and V2 systems (prior to the controls retrofit) to provide insights into the accuracy of program models. To do this, we used an ordinary least squares (OLS) regression model, shown in Equation 3. The coefficients on the engineering model estimate and the interaction variable will provide insights into the relationship between the REM/Rate model prediction for each system type and the actual energy usage of the homes when occupied.

Equation 3: Normalized Electricity Comparison OLS Regression Model

$$NormkWh_i = \beta_0 + \beta_e EngkWh_i + \sum_{s=1}^{3} \beta_s System_i + \sum_{es=1}^{3} \beta_{sc} (EngkWh * System)_i + \varepsilon_{i,t}$$

Where :

$NormkWh_i$ = Normalized daily electricity usage, for home i

$EngkWh_i$ = Engineering model estimated daily electricity usage, for home i

$System_{i,t}$ = Set of binary variables indicating which air distribution system home i has

$EngkWh * System$ = Interaction between engineering estimate and the system type

β = Model coefficients, determined by the regression

ε = Regression residual, assumed to be normally distributed

In each instance where we compute metrics from coefficients estimated in a regression model, we relied on the delta method to determine the standard error, accounting for any transformations performed on the coefficients.

In the next section we provide detailed evaluation findings.

4 Evaluation Findings

4.1 Pilot Data and Analysis Review

The New Homes DHP Pilot's monitoring research study, conducted by the PMC, consisted of monitoring V2 DHP systems at 19 recently constructed homes in Oregon. The PMC installed runtime meters and temperature sensors in all 19 homes and added fan controls in four of the 19 homes as part of a subsequent test. These data were summarized in a report to Energy Trust and the data were made available to Evergreen for review and additional analysis.

The available data from the New Homes DHP Pilot was generally sufficient for our analysis, with the exception of data from the outdoor unit runtime monitors. These meters failed in the field and thus there is no available data. The purpose of the runtime data was to assess the impact of the fan control retrofits on V2 DHP systems.[2] The billing data provided the basis for the majority of the analysis presented in Section 3.2.4, with results of the analysis presented in Section 4.4. Neither the data provided by the PMC nor the report contained any information regarding V1 or V2 DHP system material or installation cost. The list of available pilot data is provided in Table 3.

[2] The evaluation was unable to assess the impact of the fan control retrofits based on real-world operating patterns. However, there is an assessment of the fan control retrofit in Section 4.4.3 that provides a basis for understanding the impacts to the system energy consumption.

Table 3: Pilot Data Provided for Evaluation

Data Type	File Name	Overview of File Content
Temperature Data	Temp Summaries.xlsx	Summary of analysis results from temperature monitoring data collected from 19 participant homes.
	19 unique Excel files, named by address (i.e., 1234 Main Street.xlsx)	Room-level temperature readings (5-min intervals), weather data (hourly), home information (floors, # bedrooms, sq. ft., HVAC brand, location of HVAC) and heat pump motor on/off times.
Billing Data	DHP Home UCI Data.xlsx	Basic site data for V1 and V2 DHP pilot homes, including address, utility, builder; monthly billing data (kWh and kW) for each site.
	Comparison Home UCI Data.xlsx	Basic site data for Non-DHP homes, including address, utility, builder; monthly billing data (kWh and kW) for each site.
Site Data	2016 and 2017 DR Horton DHP and all non-DHP homes_12.12.17.xlsx	Data on both 2016 and 2017 DR Horton DHP and non-DHP homes. The data includes heating equipment, address information, and a V2 DHP flag.
	DHP Home EPS Project Data.xlsx	DHP home data, including site address, weather station, utility information, incentive amount, HVAC measure characteristics and Energy Performance Scores. "Installed Cost" variable was $0 or blank for all records.
	Comparison Home EPS Project Data.xlsx	Comparison home data, including site address, weather station, utility information, incentive amount, HVAC measure characteristics, and Energy Performance Scores. "Installed Cost" variable was $0 or blank for all records.

Evergreen noted a number of additional concerns with the approach and outcomes, including:

- **The heating season was *not included* in the fan control retrofit assessment.** There was continuous fan operation during the entire heating season. It is impossible to assess whether the fan control strategy would work better, worse, or the same as it did during the cooling season.
- **Meters were *removed early* from three sites prior to the desired August removal timeframe.** This is the result of "real-world" monitoring and not a failure of the pilot program; the occupants at each home moved during the study period.
- **Numerous meters failed, providing *limited or no data*.**
- **Homes that received fan control retrofits appear *biased*,** as the pilot identified only very satisfied and very dissatisfied occupants as candidates for the retrofit.

However, given that this was a pilot with a limited scope, these sites may provide more information rich case studies. The report does not address this potential source of bias.

- **Occupants with fan controls were *assumed* to follow instructions from the PMC.** They were instructed not to use the controls during certain periods, but permitted to do so during other periods. It is possible that some occupants did not follow instructions.

The above concerns limit the representativeness of the final results of the pilot study in making generalizable conclusions regarding the V1 and V2 DHP systems. However, there is also a lot of very good information contained in the PMC's report. In particular, the report does a very good job documenting the temperature differential issue, providing sufficient relevant evidence to inform Energy Trust decision makers regarding the real concerns around occupant comfort levels.

4.2 Interview Results

This section presents the findings from program staff interviews, interviews with installers, and a ride-along during a V2 DHP system installation.

4.2.1 Program Staff Interviews

Evergreen conducted interviews with New Homes DHP Pilot program staff members from Energy Trust of Oregon and the PMC, CLEAResult. In total, we conducted six interviews with staff in various roles relating to the New Homes DHP Pilot. As noted in Section 3.2.2, the interviews focused on program design and implementation, data collection and analysis methods, interpretation of findings, and successes, challenges, lessons learned, and future plans as a result of the pilot. Our findings from these interviews are summarized below.

Program Design and Implementation

In general, the New Homes DHP Pilot program appears to have operated well. Communication and coordination among Energy Trust and PMC staff members were generally described as efficient and useful. For the first six months leading up to the launch of the pilot, Energy Trust and the PMC engaged in recurring bi-weekly meetings. Thereafter, the two staffs conducted occasional check-ins, as needed.

For recruitment, The PMC sent letters to homes previously identified by an installation contractor as homes with a V2 DHP system installed. The recruitment letters described in detail the objectives of the study, how and why the home is useful to the research, and the incentives offered for participation. Although the target number of participants was ultimately reached, there were some challenges associated with recruitment efforts. Noted challenges included the inability (or slow response) by the installation contractor to confirm addresses and how to appropriately communicate the pilot program to participants. In addition to recruitment letters, program staff also reported conducting recruitment phone calls and direct door-to-door outreach in order to meet the minimum target number of homes.

In addition to the temperature-monitoring portion of the pilot, the program staff identified four participant households—two that were satisfied with the V2 system and two that were unsatisfied with the system—to further their involvement in the pilot and take part in the intermittent distribution fan controls retrofit portion of the pilot. As noted by program staff, the objective of this portion of the pilot was to see if adding the controls to the fans would maintain comfortable levels of temperature distribution throughout the participants' homes.

Installation of the fan controls retrofit was thought to be easy for the electrician, with one pilot staff member ranking it a 2 out of 5, with 1 "being not at all difficult" and 5 being "extremely difficult." Additionally, the same staff member rated the customers understanding of the fan controls and their purpose as a 4 out of 5, with 1 being "did not understand at all," and 5 being "fully understood."

Data Collection and Analysis Methods

Program staff members reported that the monitoring study has been running smoothly and has encountered only minimal challenges. Reported challenges included:

- A small subset of data loggers that had failed due to unexpectedly short battery lives. The data loggers were not replaced in order to try and minimize homeowner interaction as much as possible.
- Between three or four meters that produced invalid and unusable data.
- Three participants moved during the pilot, resulting in program staff removing the monitoring equipment at the homeowners' request.

As reported by the interviewed staff members, the collected data is intended to help inform energy savings assumptions of V2 DHP systems; help create a better understanding of the best application of the system design; and incorporate changes to the monitoring guidelines, if needed, based on the outcomes of the pilot study.

In terms of any planned or desired changes resulting from lessons learned, one staff member reported that fan controls should be installed to reduce energy consumption. They based this assessment on the results of the temperature analysis, which, according to the staff member, found no difference in temperature distribution from a normal V2 system versus one with fan controls. Another staff member noted it is difficult to assess what would need to be changed at this time, citing a lack of sufficient evidence for changes.

Interpretation of Findings

Program staff reported mixed opinions regarding whether V2 DHP systems produce acceptable levels of thermal comfort for home occupants. Of the six interviewees, two each reported acceptable levels of comfort, unacceptable levels of comfort, and not having the necessary information to answer the question.

The justifications provided by the two staff members that believe the V2 system does not produce acceptable levels of thermal comfort for the occupants were based on occupant complaints. Specifically, while talking with the homeowners there were complaints regarding the noise level of the system and the temperature distribution from room to room. Interestingly, the justifications provided by the staff members who said that theV2 systems did produce acceptable levels of comfort reported the exact opposite with respect to temperature distribution (they did not provide an evaluation of the noise levels).

Overall, staff members reported that satisfaction among pilot participants with V2 DHP systems varied, with some occupants satisfied and others not; however, it was noted that the least satisfied homes initially had V1 systems installed but later upgraded to a V2 system, requiring numerous visits by contractors.

Another objective of the interviews was to assess whether the fans represent a significant energy penalty and if so, whether the intermittent fan operation—using fan controls—would also produce acceptable comfort levels for the home occupants while using less energy. The two staff members who had a definitive response to this question believed that the fan control approach would prove successful.

Successes, Challenges, Lessons Learned, and Future Plans

Although not all interviewed program staff were able to provide insight on what was thought to be the successes of the pilot, most did note that the pilot as a whole went well. The successes mentioned by program staff included:

- "The structure of the pilot was easy to follow. It was easy to get a sample population, working with two or three builders was helpful, and recruitment went well enough."
- "The temperature distribution study and the comparison between continuous run-time versus intermittent run-time are going particularly well."
- "From an engagement standpoint, once recruitment passed, we did a good job scheduling and installing the equipment, collecting the data, and finally uninstalling the equipment as well."

Similar to successes, not all program staff members were able to provide insight regarding the specific challenges; however, three staff members were able to elaborate on the most significant challenges that the pilot study had faced. The specific challenges mentioned by program staff included:

- "The timeframe for the pilot. The time it would take to test these would take too long and we would have close to two years to develop, implement and evaluate the pilot. We would like to take this information and incorporate it into program design guidelines and we initially extended the timeframe when we added the cooling system midway through."
- "We would have liked to get five to ten more houses in the study and find a permanent solution for controllers and the evaluation of the run-time systems. There were three or four meters that came back with invalid data that we were unable to use."
- "The startup was challenging, mainly agreeing upon the design, understanding what questions were being posed, and adding on secondary aspects to the pilot."

At the time of the interviews there were no planned program changes as a result of what has been learned so far. One staff member mentioned that the results of the pilot would ideally be used to inform how program staff could better support trade allies in the future.

4.2.2 Installer Interviews and Site Visit

This section presents the findings from the installer interviews and the site visit.

Pilot DHP Systems

The DHP system installer reported almost no negative feedback regarding the V2 DHP system except for some limited complaints about noise. The installer reports that the V2 system is an improvement on the V1 system, which was less capable of effectively heating and cooling second stories. The purpose of both the V1 and V2 DHP systems is to get highly efficient heat pump technologies into homes at a lower cost than a traditional ducted heat pump system.

The DHP installer also reported that an upcoming version 3 DHP system would improve upon the V2 system since it will be engineered entirely from the manufacturer as opposed to being more of a custom design. The version 3 DHP system will also come in various sizes, from one to three tons of capacity.

In terms of system costs, the DHP systems installer reported that the typical material costs of a V2 system for a 2,000 square foot house is approximately $2,000 to $2,700. Installation labor costs add between $1,100 and $1,500. The cost to install a V2 DHP system is reportedly highly dependent on the layout and size of the house. The installer also noted that the upcoming version 3 DHP system would cost approximately $500 more in equipment costs (labor costs would remain about the same).

Fan Control Addition

Regarding the fan controls addition to the V2 DHP system, the electrician controls installer reported that programming the controls was difficult and not always logical (noting that "on" meant "off" in some instances). The electrician noted that they were in disbelief that the fan system was initially designed to run constantly. The DHP system installer also noted that it is not a common practice to have fans running all the time for a heat pump system, but that the controls options on the market were either insufficient or expensive. The DHP system installer reported that the addition of controls reduced occupant comfort.

The controls installer reported that the cost of the controls was about $200 for materials and that it would take approximately three hours of labor to install. For the DHP Pilot, electricians charged $100 per hour, so the overall controls installation cost approximately $500 in total.

Installation Site Visit

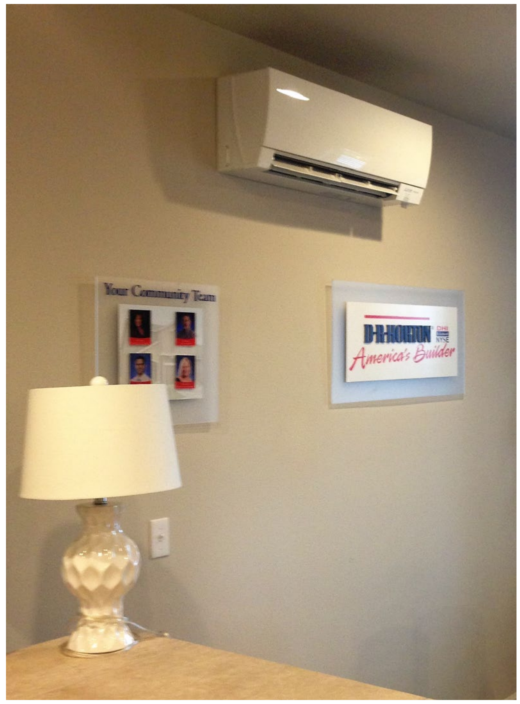
The installation site visit occurred on April 10, 2018, at a two-story townhome. There are two outdoor units and two indoor units in the home, with one indoor unit on each floor. The DHP on the first floor was installed as a traditional DHP system, with the upstairs indoor unit ducted to serve multiple rooms on the second floor.

The PMC monitored the outdoor units using runtime loggers (that ultimately did not provide valid data). One of the two outdoor units is shown in Figure 1.

Figure 1: DHP Outdoor Unit

The first floor DHP is shown in Figure 2. It is a traditional DHP with no ducting.

Figure 2: First Story "Traditional" DHP

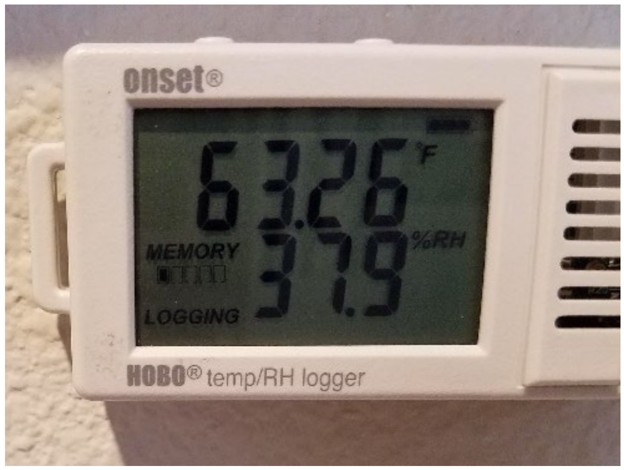


The second story ducted DHP is shown in Figure 3 (left image). There are vents above the DHP unit leading to the internal ducting. Although uncommon, at this particular site there are also vents above the door (right image) to draw air from the area directly outside the room where the DHP indoor unit is located. A programmable thermostat that is located in a utility room controls the indoor units. The occupants cell phone is used to control the thermostat.

Figure 3: Second Story Pilot DHP System and Intake Venting

Temperature and relative humidity meters were installed in the home to measure room and hallways temperatures. An example meter is shown in Figure 4.

Figure 4: Temperature and Relative Humidity Meter



During the site visit, the Evergreen staff member was able to view the exposed ducting of the DHP system. The ducting is routed through the attic and wrapped in insulation, as shown in the left image of Figure 5. The right image shows the box where a fan is installed to move air through the ducting, from the indoor unit to registers in other rooms on the second floor.

Figure 5: Upstairs Unit Ducting and Fan Box

We solicited feedback from the homeowner, electrician, and the PMC while at the home.

The homeowner was not very satisfied with upstairs unit. Their major complaints were the sound of the fans and that they are unable to control the fans (they run continuously). Prior to the installation of the fans, there were significant temperature differences, with the second bedroom receiving inadequate heating. The homeowner reported that even with fans there is a temperature difference between the master and second bedroom, which negatively affects their overall comfort level. The homeowner did report that the PMC was great to work with, that they were happy to have been in the project, and that the unit works well, but that the noise and temperature differences make it less than satisfactory. Comparatively, the homeowner reported that the downstairs, traditional DHP unit worked well.

According to the electrician, the fans are easy to install. They reported a slight learning curve, but after the first installation the process went very smoothly.

The PMC staff member confirmed that complaints about noise and temperature differences were common among homes with the ducted DHP units.

4.3 Household Survey Results

Findings from the household survey are presented in this section. Table 4 shows the populations and number of surveys completed across the three heating systems. In general, occupants reported mixed experiences and mediocre levels of satisfaction with the V1 and V2 DHP systems, on average. Some occupants were pleased while others were very disappointed in the performance of the system and comfort in their home.

Table 4: Occupant Survey Completes and Sample Size

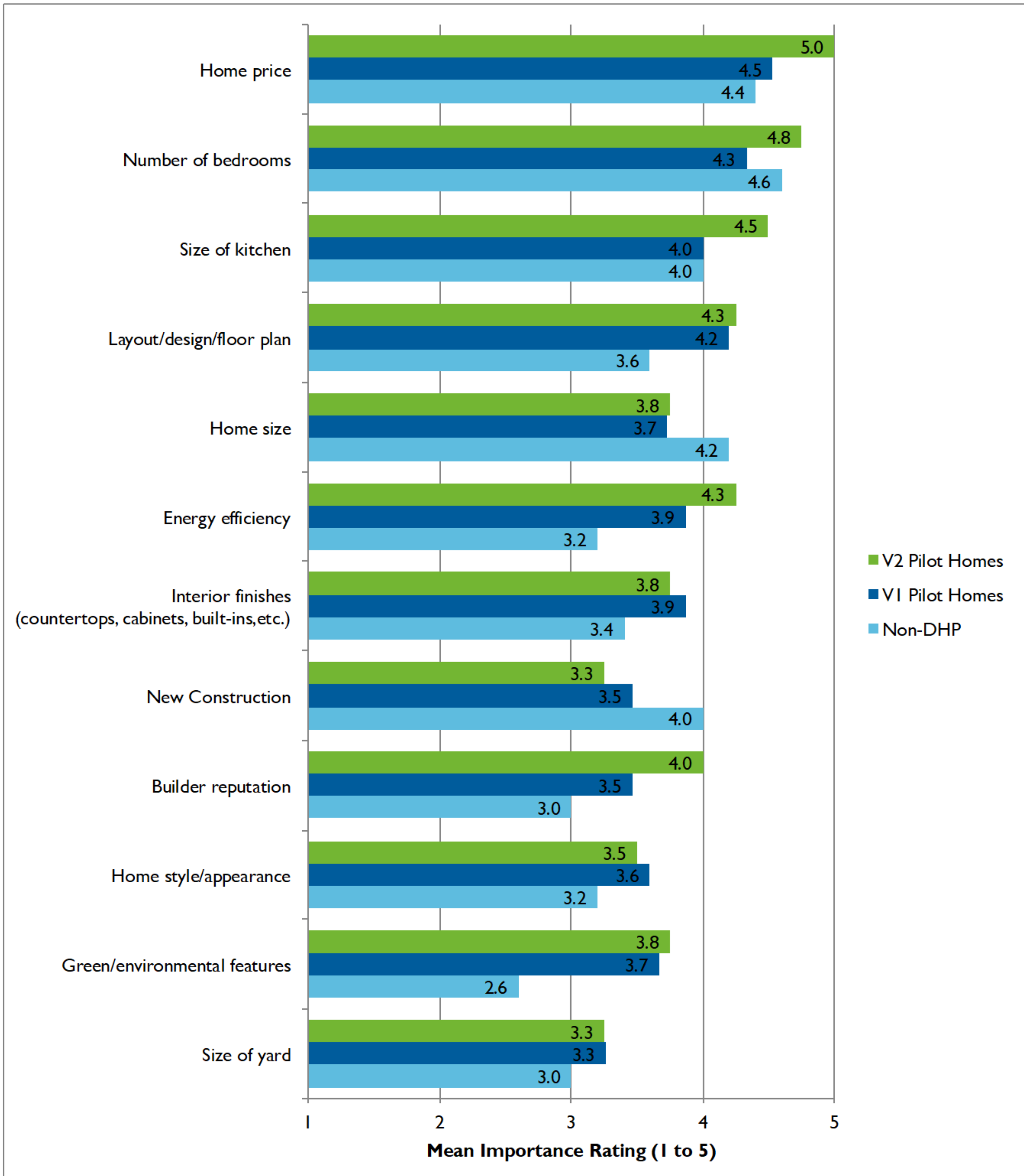
Respondent Group	Number of Completed Surveys	Number of Invite Letters Sent
Occupants of V2 DHP Pilot Homes	4	130
Occupants of V1 DHP Pilot Homes	15	300
Occupants of Non-DHP Homes	5	300

4.3.1 Motivations for Home Purchase

The price of the home and the number of bedrooms and bathrooms were the two most important attributes in respondents' decision to buy their homes, on average. Energy efficiency was most important to occupants of pilot homes with V2 DHP systems, followed by occupants with V1 systems (less so for occupants of non-DHP homes). Figure 6 provides a breakdown of mean importance of various home attributes on the occupants' decisions to purchase their homes. Results are provided on a scale of 1 to 5 where 1 is "not at all important" and 5 is "very important", by respondent group.[3]

[3] The figure omits categories with low reported levels of importance: landscaping, presence of porches, presence of a home office, presence of home entertainment/media room, and presence of a pool/hot tub.

Figure 6: Mean Importance of Home Attributes



4.3.2 DHP System Characteristics

Table 5 shows the locations of DHP indoor units in survey respondents' homes. Most were located in living rooms and bedrooms, with a limited number installed in hallways, kitchens and utility rooms, and with one installed in an upstairs den.[4]

Table 5: Location of DHP Systems

Room	V1 Pilot Homes	V2 Pilot Homes
Living Room	11	4
Bedroom	12	
Hall	2	1
Kitchen	2	
Utility Room		2
Den		1

The survey asked respondents what type of thermostat controls are used to set the temperature of their DHP systems on both the first and second floors of their homes. Occupants with V2 DHP systems reported that they control their systems using either a programmable digital thermostat or a programmable handheld controller. In addition to those control types, occupants with V1 DHP systems reported using manual handheld controllers, mechanical thermostats, and digital non-programmable thermostats. The majority of occupants with V1 systems use a programmable handheld controller.

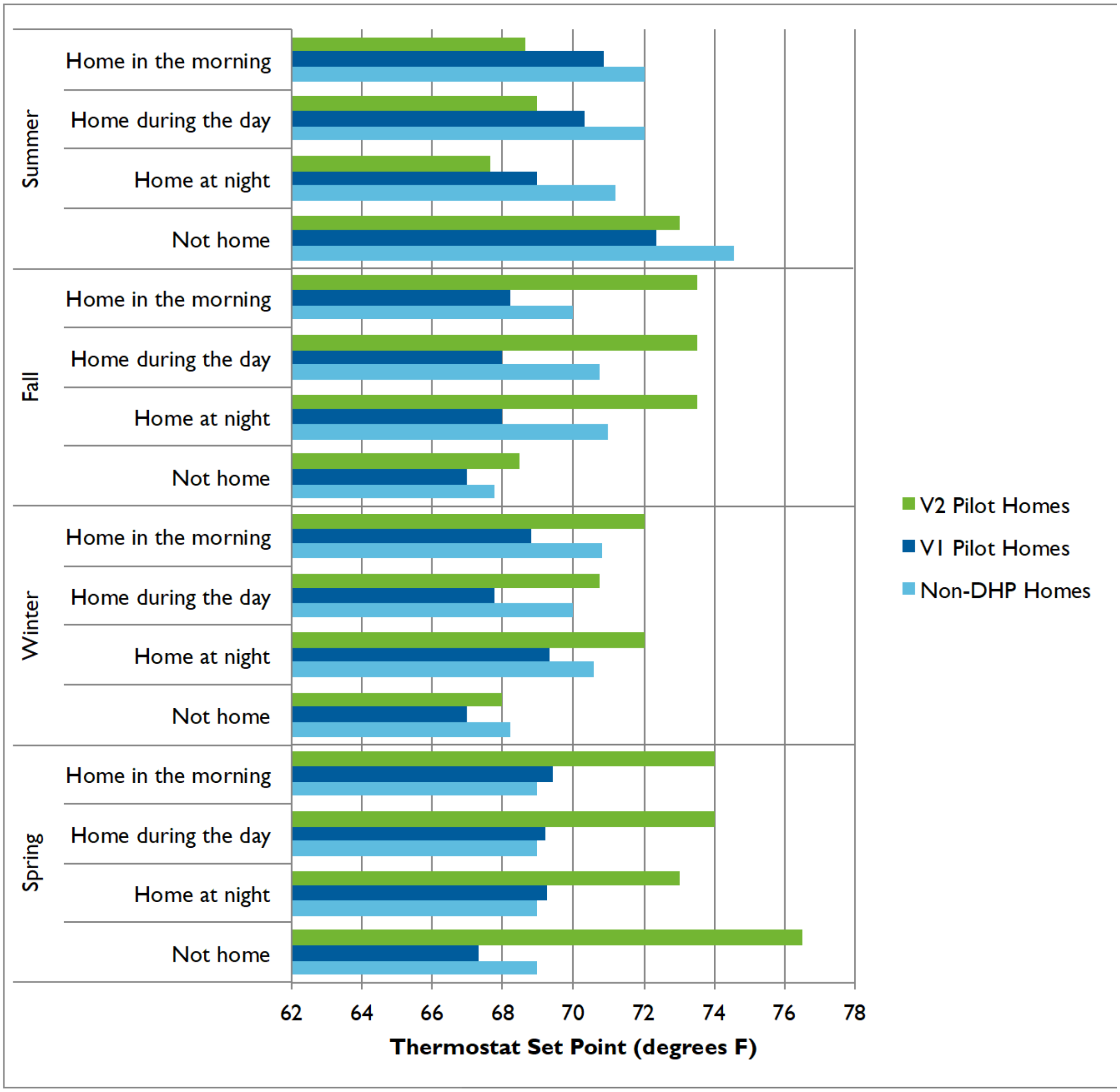
Additionally, survey respondents were asked about thermostat set points on the first and second floors of their home during the summer, fall, winter and spring seasons during various times during the day including: in the morning when home, during the day when home, at night when home, and when not at home. Set points varied from a low of around 60 degrees and highs around 75 degrees, with a small number of respondents reporting that they either let the temperature rise above 80 degrees in the spring and summer or that they heat their home above 80 degrees when they are home during winter evenings.

Figure 7 shows the mean temperature set points, by respondent group. Occupants with V2 DHP systems reported the highest set points while home in winter and the lowest set points in the summer. Occupants of non-DHP homes reported the lowest set points in the winter and highest in summer (while at home). This is indicative of either performance

[4] This represents a count of homes; some v1 homes reported multiple DHP systems, indicating that they may be counting indoor heads of a standard DHP and not a v1 DHP system.

issues with the equipment or a quasi "rebound effect,"[5] where the efficiency gains of an energy efficiency measure (i.e., the V2 DHP system) leads to lower system operating costs, which can lead to an *increase in* usage relative to the comparison homes (i.e., not relative to prior usage).

Figure 7: Thermostat Set Points

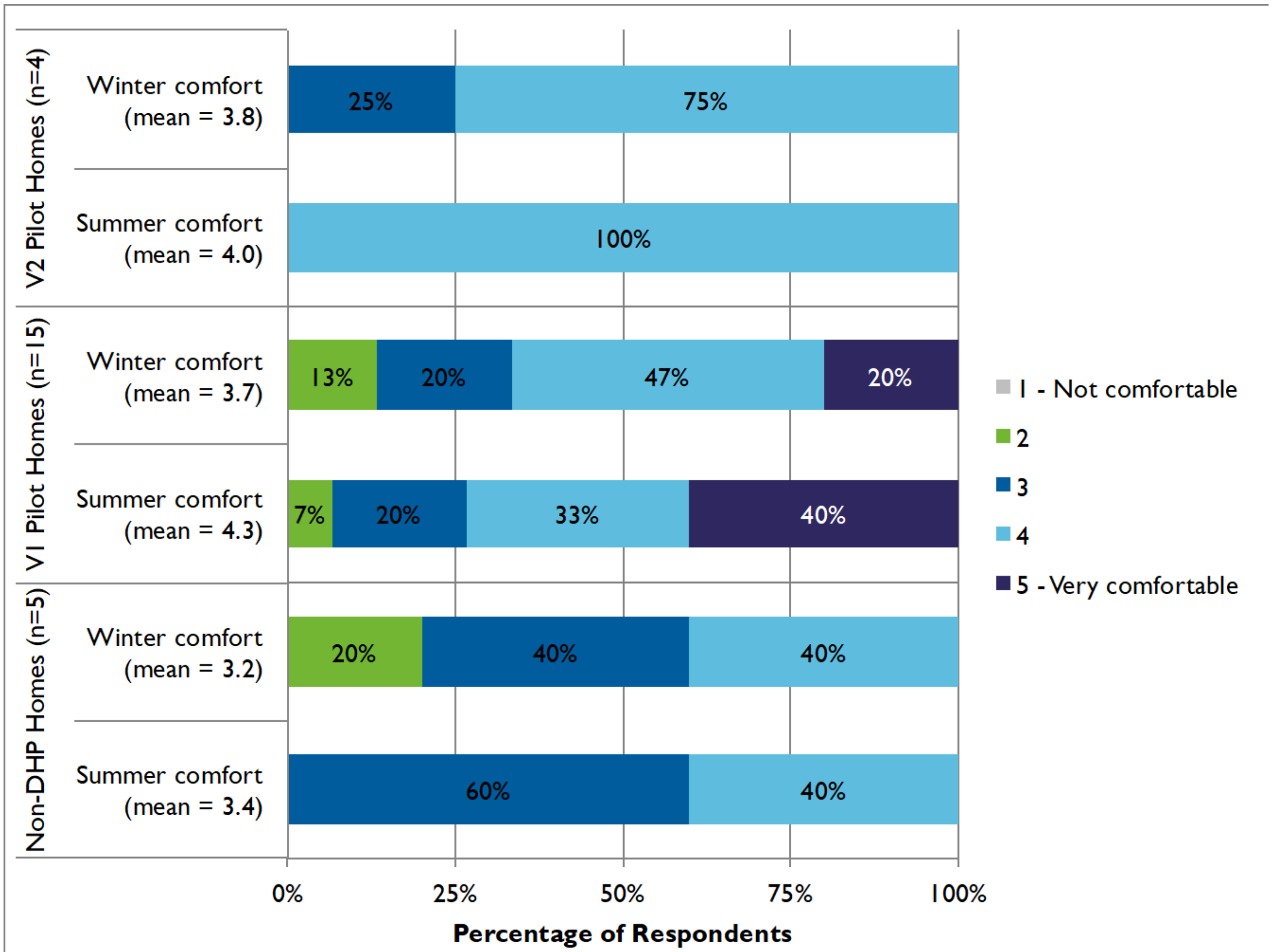


[5] For additional information: https://aceee.org/files/pdf/white-paper/rebound-large-and-small.pdf

4.3.3 Occupant Comfort

Web survey respondents were asked to rank the comfort level of their home in the winter and summer on a scale of 1 to 5, with 1 being "not comfortable" and 5 being "very comfortable." Figure 8 shows mean comfort levels in the summer and winter, by occupant group. In general, the occupants of pilot homes reported similar levels of comfort in the winter and summer. A small number of occupants with V1 systems reported discomfort (a rating of 1 or 2), but others reported high levels of comfort. Occupants of non-DHP homes reported slightly lower levels of comfort (not a statistically significant difference).

Figure 8: Seasonal Comfort Comparison



Survey respondents were also asked about their use of supplemental heating and cooling, and were allowed to provide multiple responses. The findings are shown in Figure 9 and Figure 10. Majorities of occupants with V2 DHP systems and non-DHP homes use no supplemental heating, and majorities of all occupant types use no supplemental cooling. Fireplaces and portable heaters were the most commonly cited sources of extra heat, and opening windows and using fans were the most commonly cited sources of extra cooling.

Figure 9: Supplemental Heating

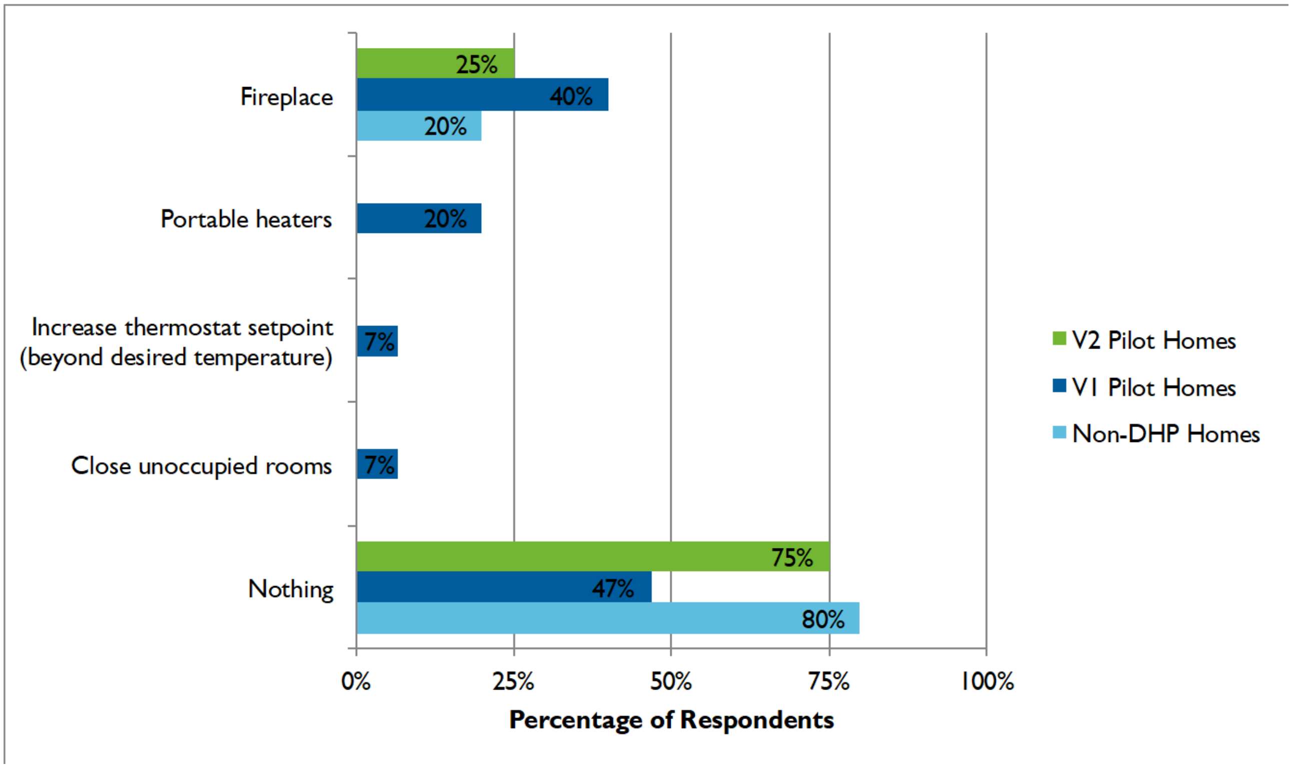
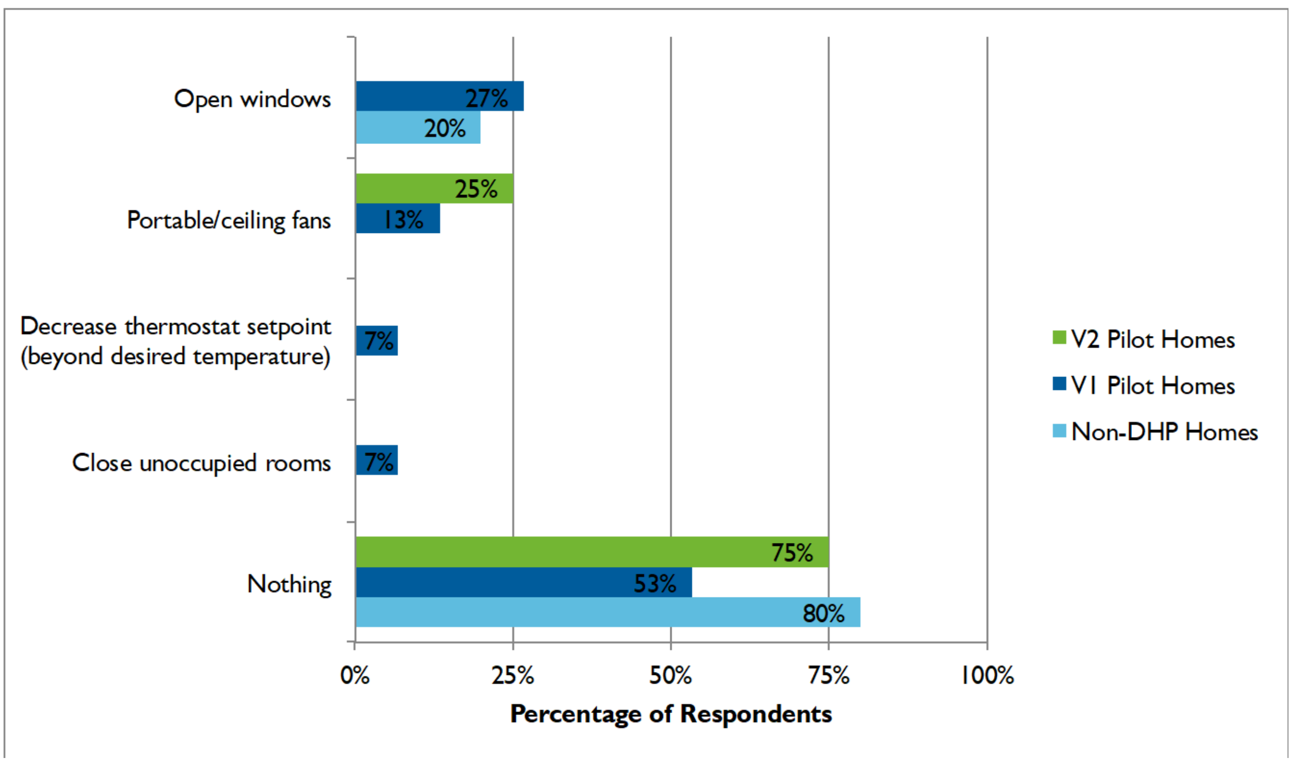


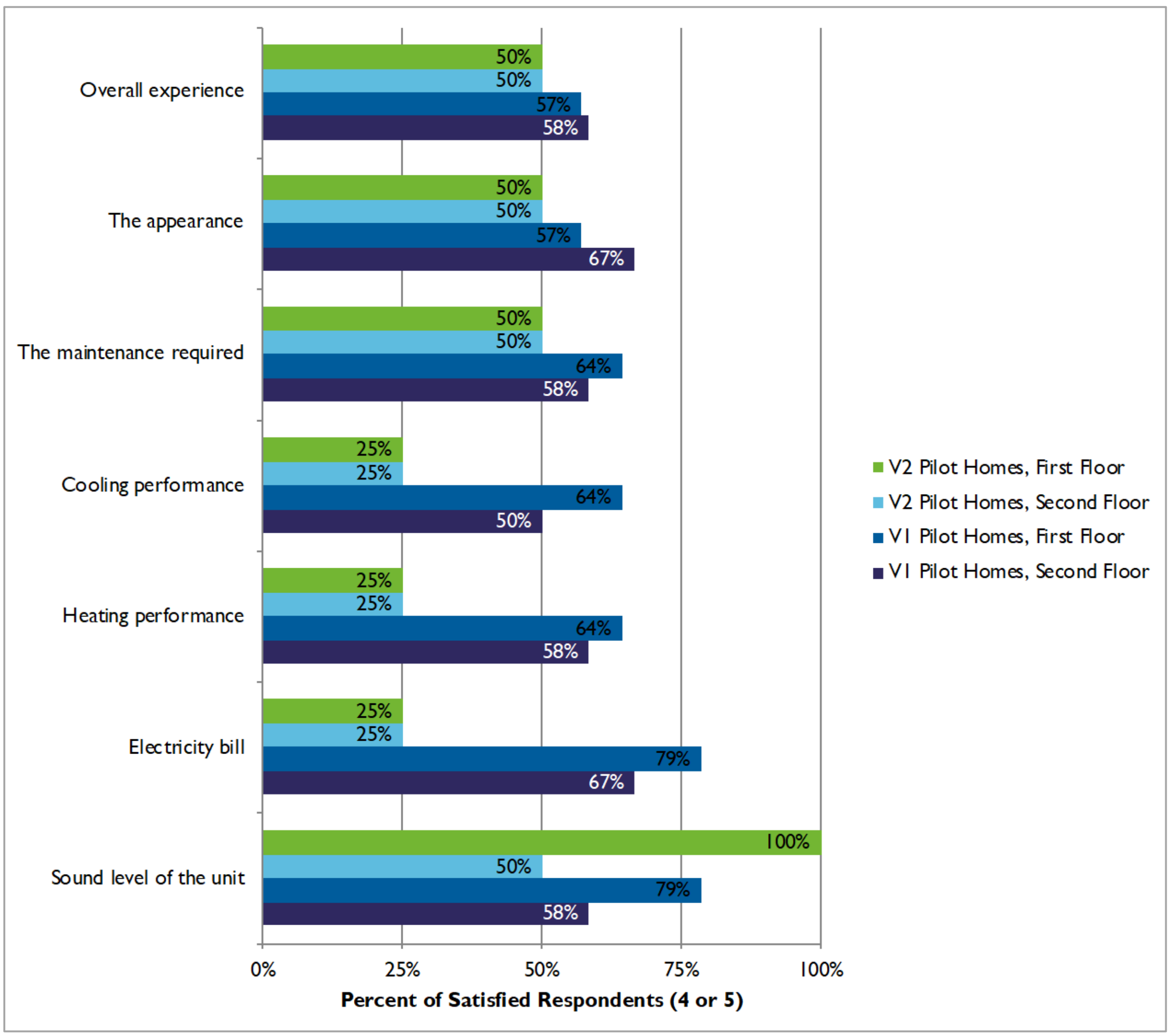
Figure 10: Supplemental Cooling



4.3.4 Satisfaction

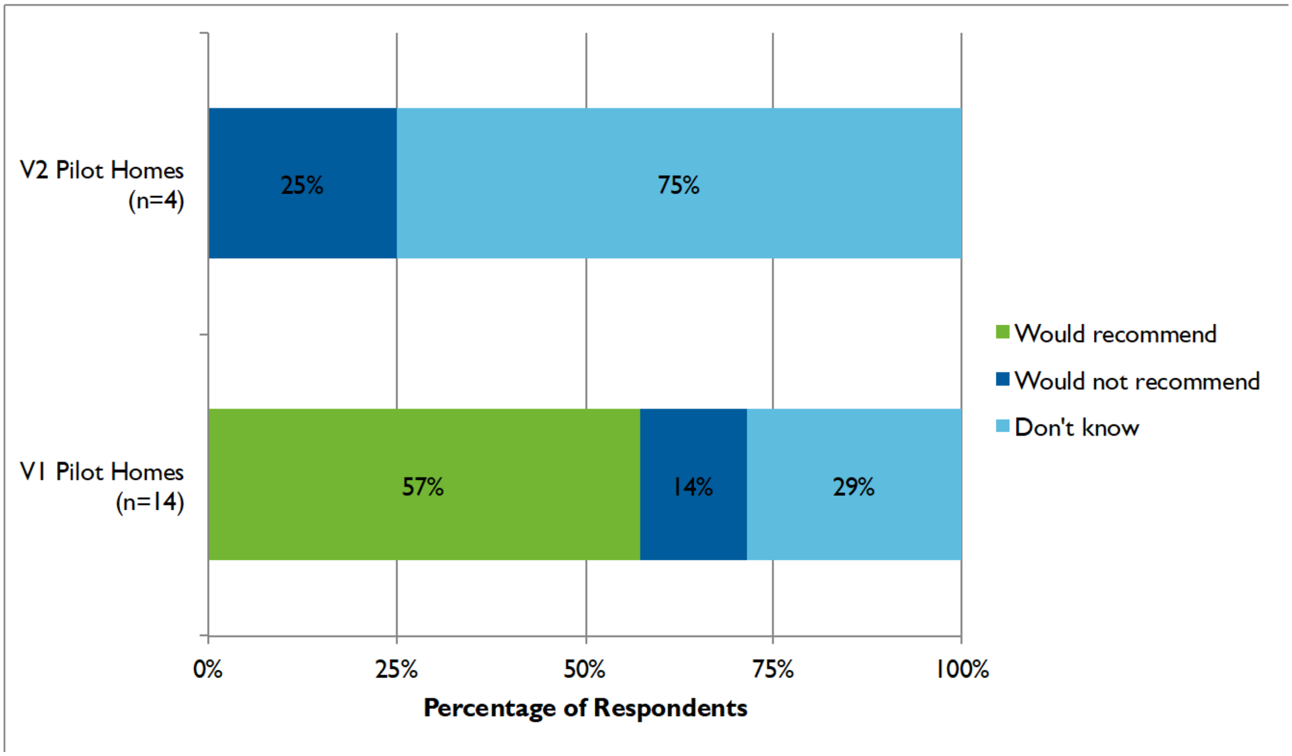
Occupants of pilot homes were asked to rate their level of satisfaction with various aspects of their homes' DHP system. Respondents provided satisfaction ratings on a scale of 1 to 5, with 1 being "not at all satisfied" and 5 being "very satisfied." Overall, the satisfaction levels were generally underwhelming, with many respondents reporting satisfaction levels of 3 ("neither satisfied nor dissatisfied") or lower for each of the metrics. Figure 11 provides detailed findings. The sound level of the unit received the highest satisfaction ratings, on average, across the first and second floor V1 and V2 systems. Comparatively, the lowest satisfaction ratings were with the V2 systems impact on respondents' electricity bill, heating performance, and cooling performance, with only 25 percent of respondents satisfied with each of the three aspects of their DHP system on both the first and second floor of their home.

Figure 11: Satisfaction Ratings



None of the occupants of V2 pilot homes would recommend a DHP system to a friend, colleague or family member (one would not, and three were unsure). A small majority of occupants of V1 pilot homes would recommend a DHP system (57 percent).

Figure 12: Would Pilot Homes Recommend a DHP System?



4.4 Billing Analysis Results

This section provides the results of the billing analysis tasks outlined in Section 3.2.4.

4.4.1 Engineering Model Performance

Figure 13 provides scatterplots for pilot homes and non-DHP homes comparing the daily electricity usage for the same weather conditions estimated by the engineering REM/Rate model (x-axis) and our billing model (y-axis). Each home is shown as a single point with the color corresponding to the primary heating fuel. If the two model estimates aligned perfectly, all of the points would fall along the diagonal line.

Figure 13: Comparison of Estimated Daily Electricity Usage by System Type

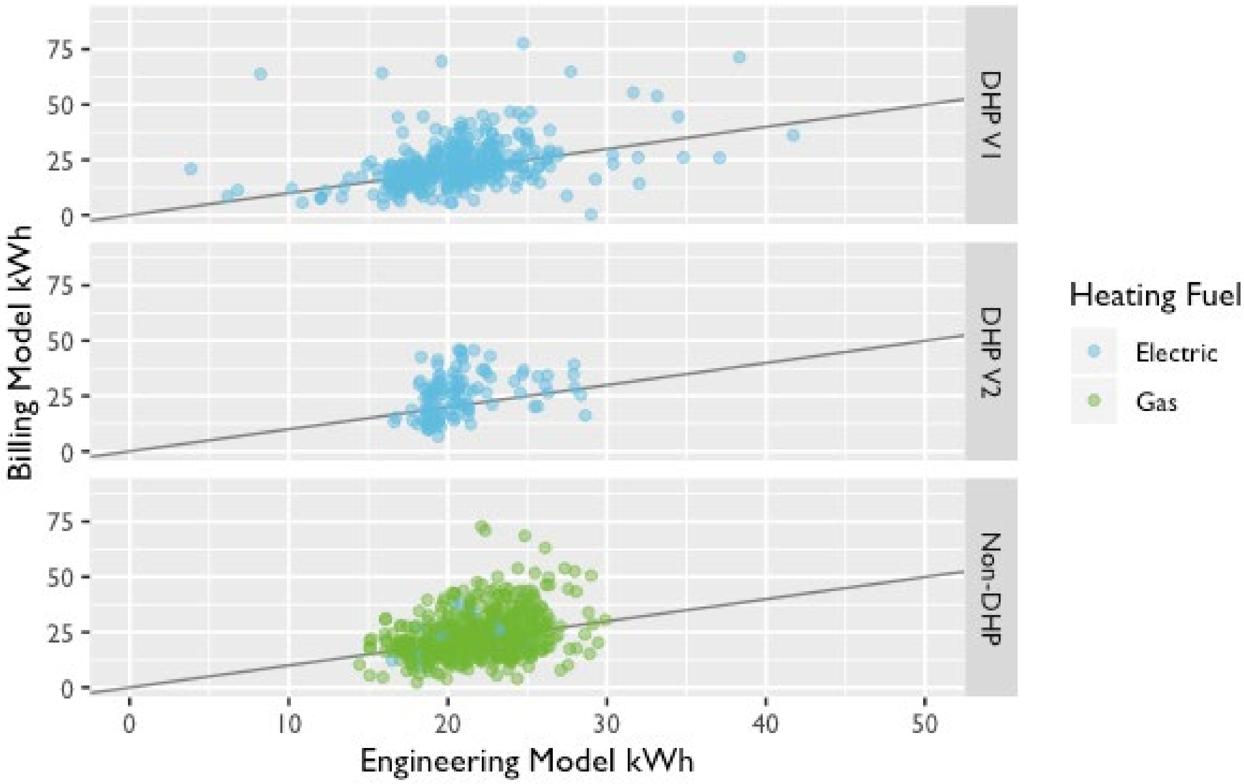


Figure 14 expands this comparison to a full year and both fuel types, converting both electricity and gas consumption into MMBtu. Once fuels are combined, it is clear that the non-DHP homes (i.e., homes with gas furnaces) are much more varied than either homes with V1 or V2 DHP systems in both the engineering predictions and billing estimates of energy usage. For all three systems, our billing estimates fall on both sides of the line, suggesting that the engineering estimates are a fairly good prediction of true energy usage.

Figure 14: Comparison of Annual Energy Usage by System Type

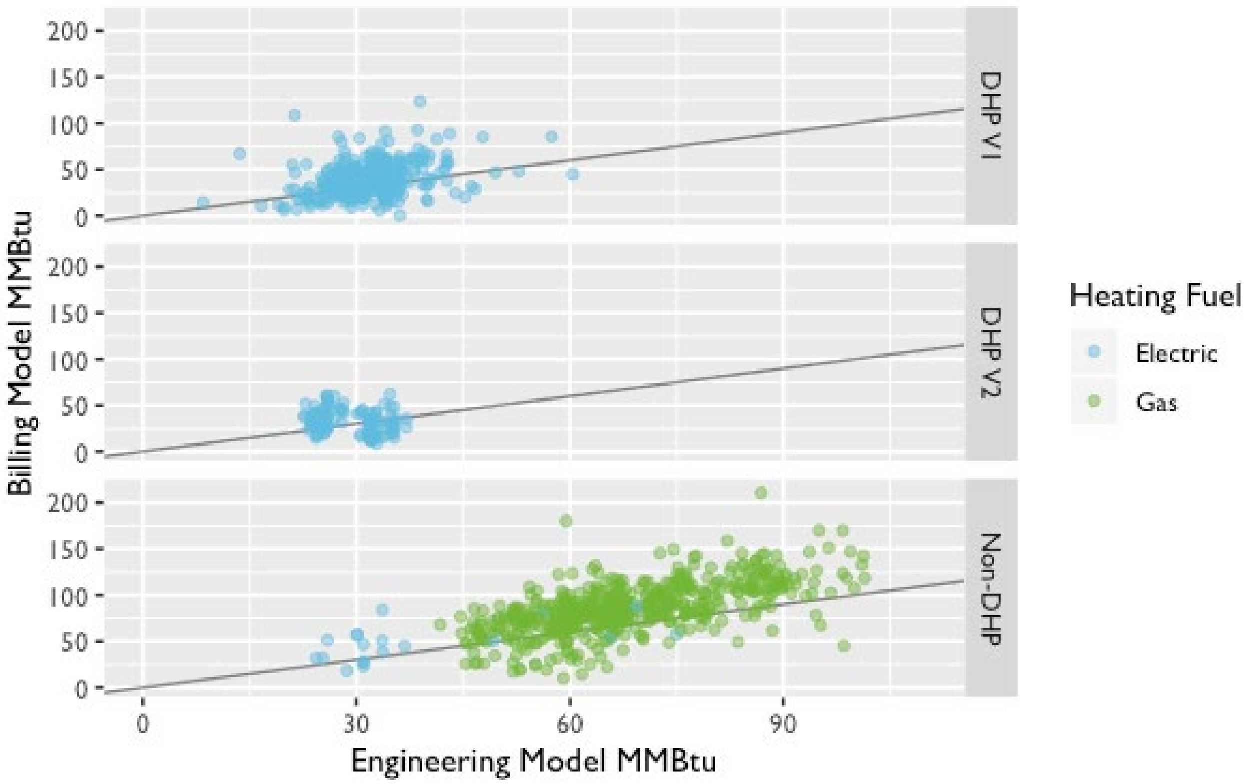


Table 6 provides known characteristics of homes retained in the billing analysis sample. The homes with V1 DHP systems are more diverse than those with V2 systems. This is consistent with the variation in engineering model predictions for electricity (kWh) and combined (MMBtu) energy usage. Variation across observations (i.e., homes) can improve the regression model's ability to extract true patterns in the data from random noise. Hence, the limited variation across homes with V2 systems will likely correspond to wider error bounds on the coefficient estimates for those systems.

Table 6: Characteristics of Homes in Sample by System Type

System Type	Building Year	Square Footage	Stories	EPS Score (90% CI)
V1 DHP	≤2017	<3,500	1-3	39.5 ± 17.8
V2 DHP	2015-2017	<2,500	1-2	38.4 ± 11.5
Retrofitted V2 DHP	2016	1,600-1,800	2	36.9 ± 3.8
Non-DHP	2015-2017	<4,000	1-3	68.0 ± 21.2

The coefficients on the engineering model estimate (β_{Eng}) and interaction variable ($\beta_{Eng*Sys}$) in the OLS regression for electricity can be used to quantify the relationship between the REM/Rate model prediction for each system type and our billing model's estimate of the actual electricity usage of the homes. Similar to a correlation, a perfect relationship would have a value of 1. Table 7 provides the coefficients and standard errors estimated with the delta method. The coefficient on the version 1 system is statistically significant and less than 1, suggesting that the engineering models overestimate the electricity usage of version 1 homes on average. Conversely, the engineering models tend to underestimate the electricity usage of version 2 homes; however, this coefficient is not statistically significant (note that the confidence interval includes 1.0).

Table 7: Relationship Between Engineering kWh Predictions and Billing kWh Estimates

System Type	Coefficient Estimate	Standard Error	90% Confidence Interval
V1 DHP	0.735	0.108	(0.558, 0.913)
V2 DHP	1.226	0.362	(0.632, 1.821)

4.4.2 Comparison of Energy Impacts (V1 versus V2)

The coefficients on the air distribution system and interaction variables provide insights into the weather conditions when differences were observed for each of the three system designs, relative to each other. Table 6 provides the coefficient estimate and standard error, estimated with the delta method, representing the incremental kWh or therms consumed for each additional heating or cooling degree-day, holding all else constant.

The first three rows show the model's estimates of the additional kWh consumed by a home during a day with one additional CDD (i.e., need to cool the home by one degree to maintain a comfortable indoor temperature). We have separate estimates for homes depending on whether they have a V1, V2, or non-DHP system. The negative coefficient for homes with V1 and V2 DHP systems suggests that these occupants are using less energy for each CDD. However, the confidence interval for the V2 coefficient ranges from negative to positive, meaning that the coefficient is not statistically significantly different from 0. These results indicate that occupants of DHP V1 and V2 homes do not consistently use their DHP systems for cooling on warm days, even though they have the option. The coefficient for non-DHP homes is positive; this suggests that these homes use additional electricity for cooling. In homes with gas furnaces, this trend is observed when occupants use separate air conditioning or ventilation equipment on hot days.

Non-DHP homes consume less electricity and more gas for each additional HDD, and more electricity for each additional CDD. The confidence interval for the estimate of electricity for CDD is much wider than for HDD. These findings are consistent with our expectations for these homes because most have a gas furnace and only a subset may have cooling equipment (e.g., central AC or window air conditioner).

Pilot homes with V2 DHP systems consume less electricity than homes with V1 systems for each HDD, but show a smaller reduction in electricity usage for each CDD (though this difference in kWh per CDD is not statistically significant). Given that these homes are located in regions with a greater need for heating than cooling in the typical year, the overall annual energy required for heating and cooling will be lower in the homes with V2 systems than those with V1 systems. This finding suggests that the difference in the DHP air distribution systems may reduce the heating runtime required to maintain a stable temperature in the home. However, this improved heating efficiency may be offset by the increase in baseline electricity required by the high-power distribution fans used in the V2 systems (especially under continuous operation), above and beyond that of the V1 bathroom-style fan.

Table 8: Billing Estimates of Incremental Energy Usage per Degree-Day

	System Type	Coefficient Estimate	Standard Error	90% Confidence Interval
Electric (kWh) per CDD	V1 DHP	-0.224	0.037	(-0.285, -0.163)
	V2 DHP	-0.077	0.086	(-0.219, 0.064)
	Non-DHP	0.090	0.037	(0.030, 0.151)
Electric (kWh) per HDD	V1 DHP	0.318	0.016	(0.292, 0.344)
	V2 DHP	0.157	0.030	(0.107, 0.207)
	Non-DHP	-0.155	0.015	(-0.179, -0.130)
Gas (therms) per HDD	V1 DHP	-0.033	0.001	(-0.035, -0.031)
	V2 DHP	-0.050	0.002	(-0.054, -0.047)
	Non-DHP	0.063	0.001	(0.061, 0.065)

The energy consumed by air distribution fans with continuous operation is reflected in the fixed effects baseline estimated for each home in the regression. This is because the electricity consumed by the fans does not vary substantially over time or with changes in weather conditions. However, these baseline estimates also account for other differences across homes and residents such as square-footage, plug-load appliances, and occupancy.

To improve the validity of a comparison between homes with V1 and V2 DHP systems, we extracted a subset of homes with V1 systems that had similar characteristics to the homes with V2 systems. This includes homes built between 2015 and 2017, as well as a maximum of two floors and 2,400 square-feet of living space. For this analysis we included all V2 homes prior to the controls retrofit, if applicable.

Table 9 provides the fixed effects baseline (per day) and normalized annual electricity usage for comparable homes with V1 and V2 systems. The average daily baseline energy usage of homes with V2 systems is 4.3 kWh higher than the baseline of homes with V1 systems, though this difference is not statistically significant. Despite the reduction in electricity consumed for heating (measured by the coefficient on HDD) in homes with V2 systems, these homes consume an average of 1,558 kWh more in the normalized year than similar homes with V1 systems. This is due, at least in part, to the additional electricity required to continuously power the fans in the air distribution system.

Table 9: Comparison of Electricity Usage by DHP Systems

	Number of Homes	Baseline kWh per Day (Fixed Effects) Average	Standard Deviation	Normalized Annual kWh Average	Standard Deviation
V1 DHP homes similar to V2	155	23.2	8.5	7,650	3,106
V2 DHP homes	170	27.5	9.5	9,208	3,482
Difference		4.3		1,558	

4.4.3 Assessing the Impacts of Controls

We only received one month of electric billing data for each of the four homes after the V2 controls retrofit in April 2018. This was insufficient to create meaningful estimates of retrofit impacts in the billing regressions. Instead, we relied on the technical specifications for the V2 systems and some assumptions about the controls to create a range of estimates for the total annual kWh impacts of the controls retrofit. These assumptions can and should be adjusted based on observed DHP run times, should this data become available.

The fans are designed to operate continuously, but can be retrofit to operate intermittently, meaning that they will only come on when they sense heating or cooling. Therefore, temperature set points and interior air temperatures dictate runtime, and thus there is expected variation from one home to the next (based on outdoor temperature, insulation levels, occupancy schedules, and occupant comfort).

The equation we use to assess the impact of fan controls based on different control factors—the proportion of time the fan is running—is shown in Equation 4.

Equation 4: Version 2 Fan Control Impacts (kWh)

$$
\begin{aligned}
&\textit{Annual}\ \mathrm{k}\textit{Wh} = \\
&\textit{RatedWattsFanA} / 1{,}000 * \textit{HoursPerYear} * \textit{ControlFactorFanA} \\
&+ \\
&\textit{RatedWattsFanB} / 1{,}000 * \textit{HoursPerYear} * \textit{ControlFactorFanB}
\end{aligned}
$$

Example control impacts are shown in Table 10 for a house with two 98W fans. The far right column, labeled “No Controls,” is representative of a V2 DHP system with two fans and no fan controls, i.e., continuous operation. The difference between the “No Controls” annual kWh values and the values from the three other example homes represents the energy implications of the controls, provided a range of assumed control factor values.

Table 10: Estimated Impact of Controls Retrofit

		Home 1	Home 2	Home 3	No Controls
Fan A	Control Factor	20%	50%	75%	100%
	Annual Energy (kWh)	172	429	644	858
Fan B	Control Factor	30%	50%	50%	100%
	Annual Energy (kWh)	258	429	429	858
Overall Annual Energy (kWh)		429	858	1,073	1,717

While it remains unclear whether occupant comfort is achievable with a fan control strategy, the energy implications may be significant.

5 Conclusions

This section is organized by research question, with answers and supporting evidence following each identified research question.

5.1 Primary Research Questions

1. **How well do the program energy models estimate the actual heating energy usage and energy savings for these types of DHP systems?**

   The engineering estimates are a fairly good prediction of true energy usage. The engineering models slightly overestimate the electricity usage of homes with V1 systems, on average. Conversely, the engineering models tend to underestimate the electricity usage of homes with V2 systems; however, the regression coefficient is not statistically significant due in part to the more homogenous nature of the homes with V2 systems in the sample. See Section 4.4.1 for additional details.

2. **Can these systems produce acceptable levels of thermal comfort for occupants?**

   V1 and V2 DHP systems, including retrofitted V2 systems, struggle to produce acceptable levels of thermal comfort for all occupants. Some occupants were satisfied, while others were very dissatisfied. Dissatisfied occupants noted significant temperature differentials across rooms. This concern was also noted as a potential downside of the DHP systems during interviews and during the site visit. Furthermore, fan noise created suboptimal overall comfort for some occupants.

3. **Can these systems produce sufficient airflow and relatively even air temperatures throughout different rooms in the home?**

   This question was addressed by the PMC with review from Evergreen. Based on findings from this evaluation, air temperature differentials across rooms must be addressed in order to ensure acceptable occupant comfort.

   The report from The PMC identifies variation in temperature greater than 2°F from room to room for many of the homes, for much of the study period (see Temperature Distribution Results starting on page 3). This is for V2 homes with no fan control retrofit. This result suggests that the systems are unable to produce even airflow throughout different rooms in the home.

4. **Can intermittent air distribution produce sufficient airflow and relatively even air temperatures throughout different rooms in the home? How does it compare with continuous operation?**

This question was addressed by the PMC with review from Evergreen. Qualitatively, the answer is that intermittent air distribution does not produce even air temperatures throughout the home. However, this was also noted as problematic for homes with continuous airflow.

The report from the PMC identifies no significant change in the evenness of air temperatures from room to room with the fan control retrofit.

Engineering estimates for energy savings may be derived for fan controls (versus continuous operation) with the availability of DHP runtime data.

5.2 Secondary Research Questions

1. **What are the equipment and installation costs of these systems?**

   Per home installation costs were not available to the evaluation team and not included in the PMC's report.

   From the interviews in this evaluation, the DHP systems installer reported that the typical material costs of a V2 system for a 2,000 square foot house would be around $2,000 to $2,700. Installation labor costs would add between $1,100 and $1,500. The cost to install a V2 system is highly dependent on the layout and size of the house.

2. **How do these systems compare with more typical DHP systems and central ducted systems in terms of energy use and cost?**

   The evaluation is unable to compare energy use of the V1 and V2 DHP systems to typical DHP systems and central ducted systems because the available baseline data came from homes with natural gas heating equipment and unknown cooling equipment. However, given that the REM/Rate models were relatively accurate in estimating energy consumption, on average, of the V1 and V2 systems, they may be used in conjunction with modeled energy consumption of DHP and central ducted systems to estimate energy savings, assuming the modeled energy use of these baseline systems is similarly accurate. Fan controls may save significant energy over the course of a year depending on the DHP runtime (the pilot failed to establish runtime estimates, however).

   In terms of system cost, there are additional equipment costs and labor costs compared to typical DHP systems. The additional costs are related to the addition of ducting and fans. Standard DHPs and both V1 and V2 DHP systems are reportedly less expensive than central ducted systems.

3. **What equipment or installation procedures will allow reliable control of the distribution system with a low incremental cost?**

It is unclear if it is possible to design a distribution system that reliably produces satisfactory occupant comfort. Some occupants reported high levels of comfort while others reported poor comfort levels. The upcoming version 3 DHP system may provide better results, but the version 3 system was not yet available to be included in the DHP Pilot.

4. **What is the difference in energy consumption for the systems with continuously versus intermittently operating air distribution systems?**

   Temperature set points and interior air temperatures dictate fan runtime for controlled fans in intermittent operation mode, and thus there is expected variation from one home to the next.

   The pilot data was insufficient to create any meaningful estimates of the impact of fan control retrofits. However, in Section 4.4.3 we provide a framework for utilizing runtime data (also unavailable to the evaluation) in order to assess the energy implications of using an intermittent fan control strategy. Fan controls have the potential to save a significant amount of energy, depending on DHP runtimes.

5. **How much time does the DHP system operate throughout the year?**

   This question was supposed to be addressed by the PMC with review from Evergreen. However, the runtime loggers failed and therefore there is no data regarding annual operating hours.

6. **How many CFM do the distribution systems deliver to each room, on average?**

   This question was addressed by the PMC with review from Evergreen. In The PMC's report, they note that each inline fan is rated at 340 CFM, and that each fan supplies air to four or five registers within the home. The report did not assess airflow directly, but rather investigated the symptoms of too much or too little airflow: large temperature differentials between rooms. Since the study found significant variation in temperatures from room to room at some homes, evidently the conclusion is that airflow did not distribute temperatures adequately across rooms. Therefore, this question is impossible to answer given the existing data.

7. **How much does it cost to add air distribution controls to these systems?**

   This question was supposed to be addressed by the PMC with review from Evergreen. However, no cost data or information was provided in CLEAResult's report or in any of the data files.

Per our electrician interview, the cost of the controls installation includes approximately $200 for materials and three hours of electrician labor at $100 per hour. The total installed cost for the controls is approximately $500.

5.3 Evaluation Recommendations

The evaluation findings demonstrate that the V1 and V2 DHP systems are unable to provide sufficient levels of occupant comfort to warrant their continued inclusion in Energy Trust of Oregon's New Homes Program. Comfort levels were acceptable to some occupants, but unacceptable to others. New Homes Program staff members and DHP system installers noted occupant comfort as a potential or realized problem, as well. A complete list of recommendations is provided next.

Evaluation recommendations include:

1. **Do not include V1 or V2 DHP systems in Energy Trust of Oregon's New Homes Program.** Occupant comfort may suffer, and thus we do not recommend that these systems are promoted by Energy Trust.

2. **Consider an additional DHP Pilot with the version 3 system.** A similar pilot approach with limited monitoring of version 3 systems is warranted. Energy Trust should contact installation contractors to discuss the version 3 system specifications and availability. Energy savings over legacy equipment (central air conditioners and electric or natural gas furnaces) and a lower upfront cost compared to central ducted heat pumps means that this type of ducted DHP system is promising. If the version 3 system performs as well as or better than the V2 DHP system in terms of energy savings, and if it leads to higher comfort levels and satisfaction among home occupants, the version 3 system may be suitable for inclusion in Energy Trust's New Homes Program. More information is needed.

3. **Work with energy monitoring contractors to ensure proper testing of monitoring equipment prior to deployment.** Run time data for version 3 systems would be important to assessing their overall performance. Run time data also would have permitted a more thorough evaluation of retrofitted V2 DHP system performance and potential energy savings (over standard V2 DHP systems).

6 Appendix

6.1 Detailed Regression Output

6.1.1 Electric Fixed Effects Regression Model

```
Oneway (individual) effect Within Model

Call:
plm::plm(formula = kwh_d ~ cdd + hdd + factor(month) + factor(system_v) +
    cdd * factor(system_v) + hdd * factor(system_v), data = subset(dta,
    fuel == "Electric" & system_v != "DHP V2, retro" & projectid %in%
        subset(duration, months >= 6 & fuel == "Electric")$pid),
    model = "within", index = c("projectid"))

Unbalanced Panel: n = 1066, T = 6-38, N = 15810

Residuals:
     Min.   1st Qu.    Median   3rd Qu.      Max.
-59.29003  -3.14383  -0.16278   2.94934 165.17055

Coefficients:
                             Estimate Std. Error  t-value  Pr(>|t|)
cdd                          0.090481   0.036752   2.4619   0.01383 *
hdd                         -0.155143   0.015003 -10.3406 < 2.2e-16 ***
factor(month)02             -3.481969   0.244998 -14.2122 < 2.2e-16 ***
factor(month)03             -4.256888   0.247766 -17.1811 < 2.2e-16 ***
factor(month)04             -7.602373   0.274198 -27.7259 < 2.2e-16 ***
factor(month)05             -8.942959   0.347383 -25.7438 < 2.2e-16 ***
factor(month)06             -9.625686   0.375864 -25.6095 < 2.2e-16 ***
factor(month)07             -7.388196   0.405078 -18.2389 < 2.2e-16 ***
factor(month)08             -4.912088   0.403485 -12.1742 < 2.2e-16 ***
factor(month)09             -6.988733   0.344902 -20.2629 < 2.2e-16 ***
factor(month)10            -10.636005   0.285584 -37.2430 < 2.2e-16 ***
factor(month)11             -8.921245   0.267864 -33.3051 < 2.2e-16 ***
factor(month)12             -3.031585   0.249685 -12.1416 < 2.2e-16 ***
cdd:factor(system_v)DHP V1  -0.314507   0.047041  -6.6858  2.38e-11 ***
cdd:factor(system_v)DHP V2  -0.167740   0.089972  -1.8644   0.06229 .
hdd:factor(system_v)DHP V1   0.473072   0.015967  29.6289 < 2.2e-16 ***
hdd:factor(system_v)DHP V2   0.312572   0.029837  10.4760 < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Total Sum of Squares:    949590
Residual Sum of Squares: 673500
R-Squared:      0.29074
Adj. R-Squared: 0.23863
F-statistic: 355.118 on 17 and 14727 DF, p-value: < 2.22e-16
```

6.1.2 Gas Fixed Effects Regression Model

```
Oneway (individual) effect Within Model
```

```
Call:
plm::plm(formula = therms_d ~ hdd + factor(month) + factor(system_v) +
    hdd * factor(system_v), data = subset(dta, fuel == "Gas" &
    system_v != "DHP V2, retro" & projectid %in% subset(duration,
    months >= 6 & fuel == "Gas")$pid), model = "within", index = c("projectid"))

Unbalanced Panel: n = 1021, T = 6-29, N = 18405

Residuals:
     Min.   1st Qu.    Median   3rd Qu.      Max.
-3.341577 -0.286113  0.013674  0.246193 11.151037

Coefficients:
                              Estimate  Std. Error  t-value  Pr(>|t|)
hdd                         0.06318809  0.00108831   58.061 < 2.2e-16 ***
factor(month)02            -0.41008726  0.01980388  -20.707 < 2.2e-16 ***
factor(month)03            -0.40176056  0.01999396  -20.094 < 2.2e-16 ***
factor(month)04            -0.80197030  0.02210972  -36.272 < 2.2e-16 ***
factor(month)05            -1.33048808  0.02483882  -53.565 < 2.2e-16 ***
factor(month)06            -1.49645180  0.02666780  -56.115 < 2.2e-16 ***
factor(month)07            -1.51303810  0.02844927  -53.184 < 2.2e-16 ***
factor(month)08            -1.59770149  0.02769893  -57.681 < 2.2e-16 ***
factor(month)09            -1.53581712  0.02802687  -54.798 < 2.2e-16 ***
factor(month)10            -1.35793546  0.02296546  -59.130 < 2.2e-16 ***
factor(month)11            -0.77934685  0.02196262  -35.485 < 2.2e-16 ***
factor(month)12            -0.33488280  0.02114543  -15.837 < 2.2e-16 ***
hdd:factor(system_v)DHP V1 -0.09633505  0.00087241 -110.424 < 2.2e-16 ***
hdd:factor(system_v)DHP V2 -0.11375929  0.00180089  -63.169 < 2.2e-16 ***
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

Total Sum of Squares:    18664
Residual Sum of Squares: 4995.1
R-Squared:      0.73237
Adj. R-Squared: 0.71644
F-statistic: 3395.19 on 14 and 17370 DF, p-value: < 2.22e-16
```

6.1.3 Normalized Electricity Comparison OLS Regression Model

```
Call:
lm(formula = annual_kwh ~ est_annual_kwh + syst + syst * est_annual_kwh,
    data = dta_comp)

Residuals:
     Min       1Q   Median       3Q      Max
-13009.6  -2220.3   -562.8   1473.0  18955.0

Coefficients:
                            Estimate Std. Error t value Pr(>|t|)
(Intercept)                2752.4740   820.8483   3.353 0.000861 ***
est_annual_kwh                0.7353     0.1079   6.816 2.77e-11 ***
systDHP V2               -2800.0016  2868.3856  -0.976 0.329470
est_annual_kwh:systDHP V2     0.4912     0.3773   1.302 0.193585
---
Signif. codes:  0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1
```

```
Residual standard error: 3594 on 487 degrees of freedom
  (174 observations deleted due to missingness)
Multiple R-squared:  0.1177,  Adjusted R-squared:  0.1123
F-statistic: 21.66 on 3 and 487 DF,  p-value: 3.474e-13
```

6.2 Program Staff Interview Guide

[Will include with final draft]

6.3 Installer Interview Guide

[Will include with final draft]

6.4 Occupant Web Survey Guide

[Will include with final draft]

6.5 Detailed Occupant Web Survey Tables

[Will include with final draft]