Pacific Northwest
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PNNL-34419

Very High Efficiency Dedicated Outdoor Air System Field Site Re-Evaluation

December 2023

Tim Yoder
Alisha Piazza
Shat Pratoomratana
Linda Sandahl

U.S. DEPARTMENT OF ENERGY

Prepared for the U.S. Department of Energy
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Summary

The study reported here evaluated the long-term performance of Very High Efficiency (VHE) Dedicated Outside Air Systems (DOASs) installed at eight sites that participated in field evaluation studies performed by the Northwest Energy Efficiency Alliance (NEEA) and Institute for Market Transformation (IMT) from 2015 through 2020. The study compared the energy performance of the systems in 2021-2022 to the findings of the original evaluations. It also evaluated the indoor environmental quality (IEQ) as perceived by occupants and building operator feedback before and after the system conversion. The findings of the study are important for building owners and managers who are considering adopting VHE DOASs. The study found that the systems:

- consistently saved energy over the long term,
- improved occupant comfort, and
- received positive feedback from building operators.

Figure S-1 shows a summary of the sites' energy savings compared to the pre-conversion system based on their utility billing data. In this evaluation all the sites had similar or improved energy savings over the pre-conversion system compared to the original evaluation savings, and only one site had a small reduction in energy savings. The sites averaged 48 percent whole site energy savings compared to the pre-conversion system. The continued energy performance of these sites provides strong evidence that the energy savings achieved by VHE DOAS retrofits will be sustained long term.

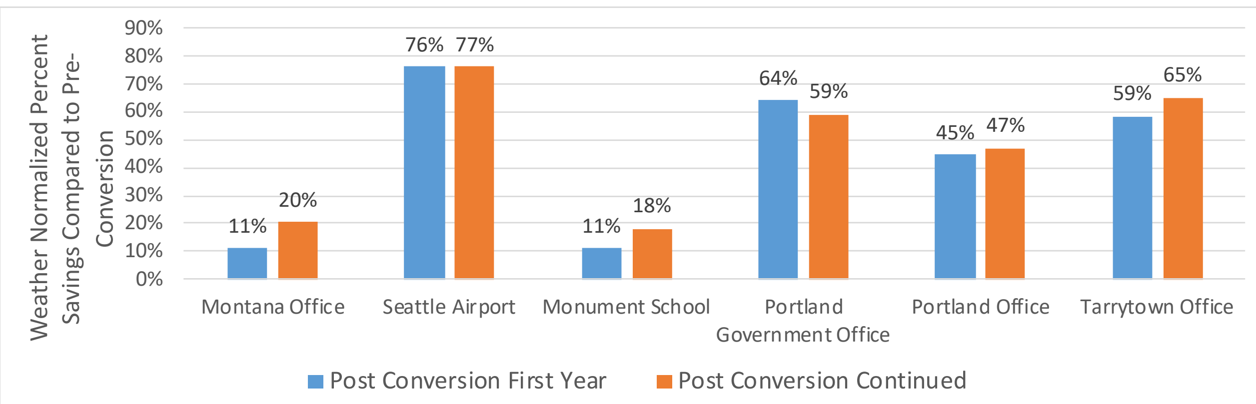

Figure S-1. Site Energy Savings from Original Evaluation and Re-Evaluation

The study also investigated the changes in occupant comfort resulting from the VHE DOAS retrofit. Responses to a survey sent to the sites' occupants revealed that the conversion resulted in a better indoor environment for the occupants. Most respondents reported that their satisfaction increased, and dissatisfaction decreased post-conversion. Overall, occupants were 43 percent more satisfied and 30 percent less dissatisfied post-conversion compared to pre-conversion.

The study's findings suggest that a VHE DOAS can be a solution to improve energy efficiency, reduce energy costs, and increase occupant comfort in buildings.

Acknowledgments

We thank the Norwest Energy Efficiency Alliance and the Institute of Market Transformation for collaborating with us throughout the entire project, sharing original findings, and consulting on the re-evaluation. We also thank Energy350 for their analysis and insights. Finally, we thank the staff from each of the demonstration sites for sharing their data, participating in surveys, and sharing their experiences.

Acronyms and Abbreviations

ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CART	Classification and Regression Trees
CV(RMSE)	coefficient of variation of the root mean square error
ERV	energy recovery ventilator
EUI	energy use intensity
DOAS	dedicated outside air system
HRV	heat recovery ventilator
HVAC	heating, ventilation, and air conditioning
IMT	Institute for Market Transformation
IEQ	Indoor Environmental Quality
ISD	Integrated Surface Database
M&V	measurement and verification
ML	machine learning
NCEI	National Centers for Environmental Information
NEEA	Northwest Energy Efficiency Alliance
NMBE	normalized mean bias error
NOAA	National Oceanic and Atmospheric Administration
PNNL	Pacific Northwest National Laboratory
RF	random forest
VHE	very high efficiency
VRF	variable refrigerant flow

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1.0 Introduction

This report presents findings from a study conducted by Pacific Northwest National Laboratory (PNNL) to evaluate the long-term performance of Very High Efficiency (VHE) Dedicated Outside Air Systems (DOASs)—also referred to as VHE heating, ventilation, and air-conditioning (HVAC) systems—installed in eight sites that participated in field evaluation studies performed by the Northwest Energy Efficiency Alliance (NEEA) and Institute for Market Transformation (IMT) from 2015–2020 (NEEA 2020). The report revisits energy performance findings from previous studies and compares them to the systems' performance in 2023. In addition, it evaluates (1) Indoor Environmental Quality (IEQ) as perceived by occupants pre- and post-system conversion, and (2) building operator feedback pre- and post-conversion. Findings related to both the long-term persistence of energy savings and occupant and building operator feedback are important considerations for building owners and managers who may be interested in installing VHE DOASs.

1.1 Technology Overview

VHE DOASs are designed around four core principles:

- High efficiency ventilation system,
- High performance conditioning system,
- Ventilation system completely decoupled from the conditioning system,
- Right-sized systems that are not oversized.

Both NEEA and IMT define the efficiency requirements of the ventilation and conditioning systems in lieu of specifying a required type of mechanical system. While their requirements do not match exactly (due to the geographical focus of each organization), they are generally aligned. The most common approach to meeting these efficiency requirements is to serve the conditioning load with heat pumps or variable refrigerant flow (VRF) and provide the ventilation with a heat recovery ventilator (HRV) or energy recovery ventilator (ERV). ERVs and HRVs are a type of packaged DOAS that are generally designed to serve small commercial or residential buildings. Figure 1 shows an illustration from NEEA (2020) that illustrates this typical configuration.

HVAC systems serve two primary purposes in a building. The first is to provide heating and cooling to keep the indoor temperature and humidity within an acceptable range, and the second is to provide adequate outdoor air for ventilation to the building occupants. Many types of HVAC systems meet both requirements with a single system. However, serving those needs with separate systems allows each system to be optimized for a single function, often offering opportunities for increased energy efficiency and occupant comfort.

HVAC systems are frequently oversized compared to the required load for a variety of reasons. There are negative operational consequences associated with systems being oversized, including negative impacts on occupant comfort, and oversizing also increases the first cost of the system. Similarly, undersizing HVAC systems can have negative performance and operational impacts. By rightsizing the HVAC systems, the operational problems can be avoided, and the first costs of the system can be reduced.

VHE DOASs can provide a number of key benefits:

- decarbonization through electrification of previous fossil fuel-based heating systems,

- energy reduction from increased HVAC system efficiency, and
- improved indoor air quality from increased ventilation rates and better temperature and humidity control.

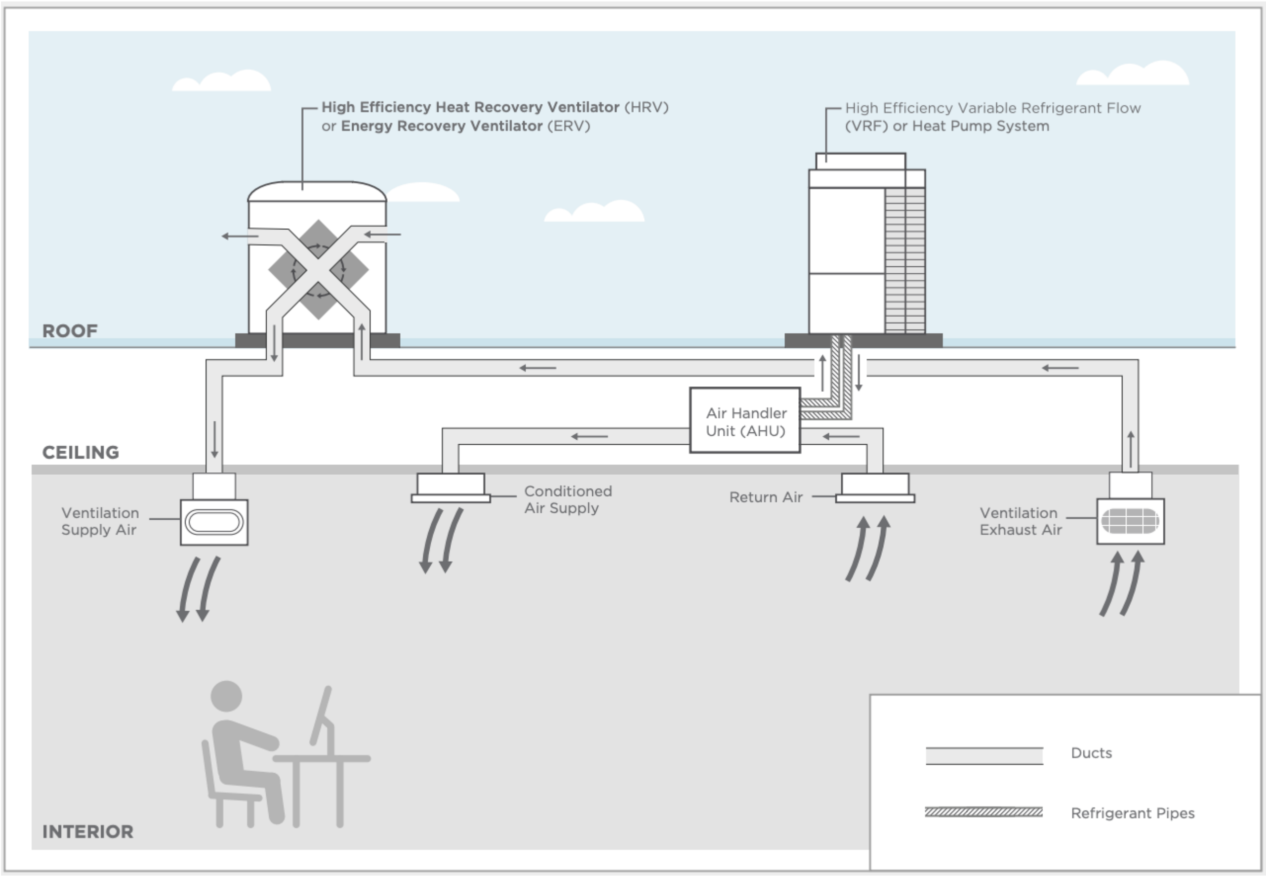

Figure 1. VHE DOAS System Concept (NEEA 2020)

1.2 Original Evaluation

From 2015–2020, NEEA completed either VHE DOAS pilots or technical assistance projects. During the same time, IMT championed efforts to complete similar projects. A total of 16 projects were evaluated to some extent. Pilot site participants saw a 70 percent reduction in their actual HVAC energy use and a 42 percent reduction in actual whole-building energy use. Even if these pilot buildings had started with standard code-minimum equipment prior to the conversion, modeling still shows significant average energy savings of 65 percent for HVAC and 36 percent for the entire building. In addition, participants reported improved indoor air quality. At several of the sites, gas-fired heating equipment was replaced with heat pumps without increasing overall electricity use or demand.

1.3 Project Objectives

The objective of this study was to evaluate the long-term performance of VHE HVAC systems, including the following actions:

- Quantify recent energy performance. Assess the performance of the system using updated utility data covering a more recent time period compared to the original analysis. This analysis investigated whether the performance demonstrated in the original reports persisted over time and whether the anticipated energy performance expectations continued to be realized.
- Assess qualitative performance. Assess the qualitative performance of the technology, including assessments of any performance, maintenance, or user issues (e.g., comfort, noise, etc.). Data sources for this assessment included occupant surveys and interviews with facility staff to assess operational strategies during COVID-19.

2.0 Measurement and Verification Methodology

This project built on the extensive measurement and verification (M&V) effort conducted as part of the original NEEA effort. This section describes the method used for the extension of that effort.

2.1 Site Descriptions

Eight commercial buildings participated in this study. Seven sites were part of the original NEEA pilot and are located in Washington, Oregon, and Montana. One site was a pilot for IMT in New York. Table 1 provides a brief summary of each site. Appendix A contains additional details about each site.

Table 1. Site Descriptions

Site Name	Occupant	State	Climate Zone	Conversion Date	Floor Area (ft^2)	Pre-Conversion HVAC System	Post-Conversion HVAC System
Montana Office	Electric Co-Op	MT	6B	August 2016	5,735	RTU, electric boiler, swamp coolers, and server room heat pump	Heat pump and HRV
Seattle Office	Engineering Office	WA	4C	September 2016	6,100	Electric RTU with electric-resistance terminal heat	VRF and HRV
Seattle Airport	County Airport	WA	4C	April 2017	25,200	Gas-electric RTUs and electric resistance	VRF and HRV
Monument School	Rural Elementary School	OR	5B	September 2020	7,200	Heat pumps supplemented with electric-resistance heaters, manual exhaust fans	Heat pump and HRV
Portland School	Urban Preschool	OR	4C	October 2020	2,900	Heat pump RTU	Heat pump and HRV
Portland Government Office	Urban Government Building	OR	4C	August 2020	20,000	Heat pumps, natural gas steam boiler, fixed-speed fans	Heat pump and HRV
Portland Office	Engineering Office	OR	4C	April 2021	11,500	Gas heat RTUs and split-system heat pump	VRF and HRV
Tarrytown Office	Property Management Company	NY	4A	September 2019	70,926	Gas heat RTUs	VRF and ERV

HRV = heat recovery ventilator; RTU = rooftop unit; VRF = variable refrigerant flow

2.2 Data Availability

Most sites metered HVAC energy use and ambient conditions for several months to years pre-conversion and post-conversion. Two sites continued to meter HVAC energy use after the initial evaluation period. Other sites provided monthly electric and, if applicable, natural gas billing data. Sites provided either whole-building data, data for the applicable portion of the building, or HVAC data only. Table 2 describes what data were available at each site.

Table 2. Site Data Availability

	Montana Office	Seattle Office	Seattle Airport	Monument School	Portland School	Portland Government Office	Portland Office	Tarrytown Office
Baseline energy model	E+	E+	E+	Cust.	Cust.	Cust.	Cust.	NA
Hourly HVAC submeter data, pre-conversion	N	N	N	N	N	Y	Y	N
Hourly whole-building meter data, pre-conversion	Y	Y	Y	Y	Y	N	N	N
Hourly HVAC submeter data, initial post-conversion	N	N	N	N	N	Y	Y	N
Hourly whole-building meter data, initial post-conversion	Y	Y	Y	Y	Y	N	N	N
Electric utility billing data	Y	Y	Y	Y	N	Y	Y	Y
Gas utility billing data	N	N	Y	N	N	Y	Y	Y
Updated hourly meter data available, continued post-conversion	N	N	N	N	Y	N	Y	N
Months of post-conversion utility data available	72	24	66	26	25	26	24	36

E+ = Energy Plus Model; Cust. = Custom Spreadsheet Model.

That National Oceanic and Atmospheric Administration's (NOAA's) National Centers for Environmental Information (NCEI) is the world's largest provider of weather and climate data. The Integrated Surface Database (ISD) consists of global hourly and synoptic observations compiled from numerous sources into a single common ASCII format and common data model. The ISD includes more than 35,000 stations worldwide, and tracks parameters such as wind speed and direction, wind gust, temperature, dew point, cloud data, sea level pressure, altimeter setting, station pressure, present weather, visibility, and precipitation. For this evaluation, only the outdoor air temperature was considered as a model input. These weather data were downloaded from the NOAA website for the nearest weather station.

The ISD is publicly accessible at https://www.ncdc.noaa.gov/isd. For this project, data were accessed via File Transfer Protocol at ftp://ftp.ncdc.noaa.gov/pub/data/noaa. The nearest station was identified for each site. The weather data were downloaded for each station for the time period extending to a year prior to the installation of the VHE HVAC system up to January 2023.

2.3 Data Normalization

The data collected for this project were provided by each site and generally provided in a unique format. To streamline the analysis process and make it more repeatable the raw data collected from each site were normalized, meaning that they were put into a common format.

The utility data were available for all but one site in approximately monthly intervals. If start and end dates were available, they were used. If unavailable, the first and last day of the month were used. If reported time periods covered multiple months, energy use was divided in proportion to the number of days in each month. There were no instances in which a full month of data was unavailable. Duplicate dates were deleted. Where monthly utility data were not available, 5-minute meter data were rolled up to monthly intervals and used as a substitute for monthly billing data. Metered data for the whole building needed to be summed across multiple sub-meters. Modeled and monthly meter data were rolled up from 15-minute intervals to hourly intervals. Weather data were provided in an hourly format and required minimal normalization. Dry-bulb temperature in degrees Fahrenheit was converted to degrees Celsius.

Additionally, the output of the energy models differed between the original pilot projects (which used EnergyPlus) and the more recent technical assistance projects (which used spreadsheet-based energy models). The output of these models was standardized to be the hourly consumption of electricity and natural gas (if applicable for the site).

2.4 Analysis Methods

This project aimed to assess both qualitative and quantitative aspects of the VHE system replacement. The quantitative analysis focused primarily on energy savings, while the qualitative assessment examined the change in operations and occupant comfort.

2.4.1 Energy Analysis

The quantitative assessment of the continued energy savings consisted of two distinct efforts. The first was to use data from the sites' monthly utility data to determine the total energy savings of the new VHE DOAS compared to the previously installed (pre-conversion) system. The second analysis consisted of using modeled energy data to compare a hypothetical code-minimum replacement of the sites' original system to a calibrated model of the new VHE system.

2.4.1.1 Utility Billing Analysis

We conducted an analysis of utility billing data for sites that provided utility bills for the pre-conversion through the post-conversion period to evaluate the persistence of the savings beyond the first-year post-conversion. Six sites had sufficient utility data available to make this comparison; the Seattle Office and the Portland School did not. Data were binned into 12-month intervals to compare annual averages; if a full 24 months of post-conversion data were not available, the last 12 months of data available were taken as the post-conversion continued period, including months that overlapped with the post-conversion first-year period. Energy use was weather normalized on an annual basis by the ratio of average to actual degree days.

2.4.1.2 Modeled Energy Analysis

While the utility billing analysis provided the energy savings of the new system compared to the previously existing system, energy models were used to estimate the savings of the new system compared to a hypothetical code-minimum system. The energy savings compared to the code-minimum system provide a better estimate of the incremental energy savings that are attributed to the VHE system over a bare-minimum replacement of the existing system, because there is no limit to how inefficient the existing systems could be in practice.

The sites had energy models for both the new VHE system and the hypothetical code-minimum replacement system that were developed previously as part of NEEA's initial analysis. Some of the buildings were modeled with EnergyPlus, while others were modeled with custom spreadsheet-based energy models. Our tasks did not have the available funds to recreate these energy models, so we used machine leaning (ML) to extend the original modeling results for an updated comparison.

Random forest (RF) models—a type of Classification and Regression Trees (CART) ML algorithm—were trained on this previous daily energy modeling results using NOAA dry-bulb temperature data and datetime attributes (month, day-of-year, and weekday/weekend) as the input features. After training, updated weather information (representing the current analysis period—July 2021–September 2022) was fed into the model to model the estimated daily energy performance of both the baseline (code-minimum) and VHE systems.

Three of the existing sites used natural gas for heating prior to the retrofit (refer to Site Descriptions). The baseline energy models for those sites were modeled as still using gas heat except for the Seattle Airport because the Seattle energy code would preclude fossil fuel heating. The natural gas use in the baseline case was modeled with an additional RF model trained on only the gas usage data. For the total energy consumption of the building, the modeled gas and electric use was added together.

During training, we used standard metrics to assess the models' prediction accuracy as recommended by the American Society of Heating, Refrigerating and Air-Conditioning Engineers (ASHRAE). The baseline model accuracy was characterized by the monthly adjusted r^2 value of the model, also known as the coefficient of determination. This metric determines how well a model predicts its target, compared to just taking the average of the target value, and is often used to evaluate regression models. The baseline models were also evaluated using the monthly CV(RMSE) metric (Coefficient of Variation of the Root Mean Square Error) and the monthly NMBE metric (Normalized Mean Bias Error), which both measure the normalized deviation of the model from the target value. Success metrics (shown in Table 3) define the threshold for a minimum accuracy a model must have to be considered sufficiently accurate.

Table 3. Machine Learning Model Validation Metrics

Objective	Metric	Success Criteria (monthly)
Baseline model accuracy	Adjusted r^2 value CV(RMSE) NMBE	$r^2 > 0.7$ CV < 25% -0.5% < NMBE < 0.5%

The baseline model accuracy metrics are defined as:

$$\overline{r^2} = 1 - (1 - r^2)\frac{n-1}{n-p-1} \tag{1}$$

where

$\overline{r^2}$ = adjusted r^2 value,
r^2 = regression score (r^2) – un-adjusted,
n = sample size, and
p = number of explanatory variables in the model.

$$CV(RMSE) = \frac{1}{\bar{y}}\, RMSE \times 100\% = \frac{1}{\bar{y}}\sqrt{\frac{\sum_{i=0}^{n-1}(y_i - \hat{y}_i)^2}{n}} \times 100\% \tag{2}$$

where

$\bar{y}$ = average value of the true series,

y_i = the true value of the i-th sample,
$\hat{y}_i$ = the predicted value of the i-th sample, and
n = sample size.

$$NMBE = \frac{1}{\bar{y}} MBE \times 100\% = \frac{1}{\bar{y}} \frac{\sum_{i=0}^{n-1}(y_i - \hat{y}_i)}{n} \times 100\% \quad (3)$$

where

$\bar{y}$ = average value of the true series,
y_i = the true value of the i-th sample,
$\hat{y}_i$ = the predicted value of the i-th sample, and
n = sample size.

2.4.2 Indoor Environmental Quality Occupant Survey

To evaluate how building occupants perceive and are affected by the HVAC system a custom survey was developed. The survey asked questions regarding thermal comfort, thermal satisfaction, air movement satisfaction, acoustic satisfaction, air quality/freshness satisfaction, and perception of maintenance activities. Questions related to thermal comfort used the ASHRAE seven-point thermal sensation scale (ASHRAE Standard 55, Section 7; 2020) from cold to hot. Satisfaction-based questions also used a seven-point scale from very dissatisfied to very satisfied, with a neutral response allowed. The IEQ parameters that building occupants were asked to assess (thermal comfort, thermal satisfaction, air movement satisfaction, acoustic satisfaction, and air quality satisfaction) were based on the much-referenced Center for the Built Environment (CBE) IEQ occupant survey (CBE 2023) and our custom survey used a similar methodology. When respondents were dissatisfied in any way with a feature, they were asked additional branching questions about the sources of their dissatisfaction using pre-defined options as well as an open-ended response. On the other hand, when occupant responses indicated neutrality or satisfaction, they were not asked additional questions about the source of their comfort. Occupants were also asked questions about the date they occupied the building. If they were occupant of the building both pre-conversion and post-conversion each question would essentially be asked twice: once to determine the experience pre-conversion and once to determine the experience post-conversion. This is done to allow analysis and comparison of occupant experience pre- and post-conversion.

Once the survey questions and methodology were defined, the survey was designed using Survey Monkey. Given that there were multiple sites and that no sites had the same “conversion date”, Survey Monkey’s “custom variables” were used for the site ID and conversion date. Doing this allowed custom URL’s to be created to be sent to each site. These custom variables also allowed responses to be filtered based on each site, and allowed for custom dates to be inserted into the questions depending on the site ID.

The complete survey with all questions is available in Appendix C.

2.4.3 Operator Questionnaire

In addition to understanding the occupants’ satisfaction with the VHE systems, the study addressed how the operators viewed the system and whether the conversion to a VHE DOAS changed the maintenance costs. Given the timing of the study, the results were likely to be affected by the changes in operation and occupancy associated with COVID-19. We developed a short questionnaire that we provided (via phone conversations or email) to the operations and maintenance (O&M) staff of the buildings.

3.0 Results

Data limitations prevented conducting parts of the analysis for some of the sites. As described in Section 2.2, some sites did not have utility billing data available and not every site responded to the surveys. As such, none of the analysis pieces cover all of the sites. Despite these limitations, the results clearly show that the findings of the original NEEA evaluation have stood up over time. All of the sites showed positive real-world and modeled savings, and the occupants generally perceived increased comfort in their indoor environment.

3.1 Energy Saving Results

We used utility billing data as one method of quantifying energy savings and the persistence of savings. Utility data were not available for the Portland School; hourly meter data were used instead and were only available for the post-conversion period. The Seattle Office occupies one floor of a 3.5 floor building. Only post-conversion whole-building data were available. The Seattle Office energy use intensity (EUI) shown in Figure 2 is the whole-building EUI.

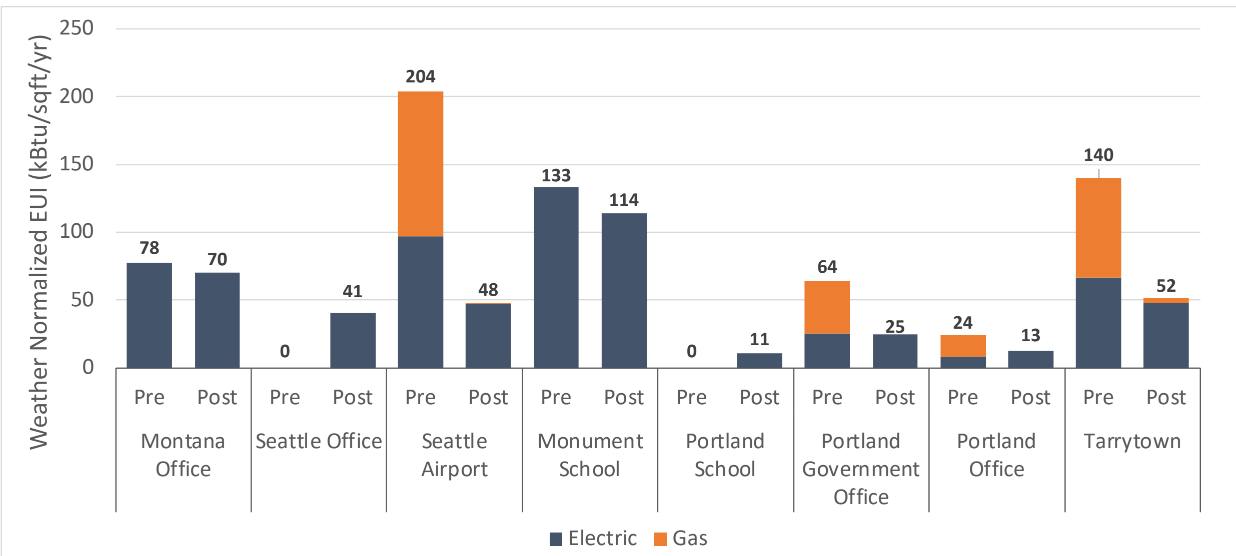

Figure 2. Pre- and Post-Conversion EUI

Figure 2 shows the pre- and post-conversion EUI for each building, if available, by energy type. Buildings that used natural gas saw a significant or complete reduction in gas use.

Figure 3 shows the persistence of energy savings post-conversion. For many sites, the initial analysis period was approximately 1 year. We continued the previous analysis with the latest available data by comparing the weather-normalized EUI reduction from the pre-conversion period. Of the sites for which pre- and post-conversion utility bills were available, the lowest energy savings were realized by the Montana Office and the Monument School with 11 percent first-year energy savings (the Monument School had an average energy savings of 15 percent during the entire available post-conversion period), and the highest energy savings were realized by the Seattle Airport (73 percent). Figure 3 shows that most sites maintained or exceeded weather-normalized first-year savings.

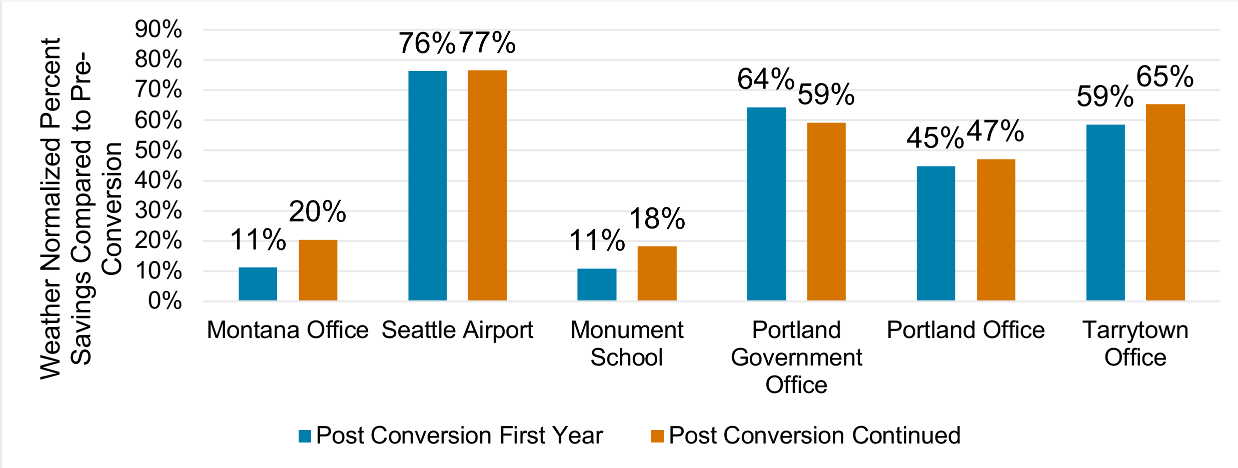

Figure 3. Persistence of Energy Savings

Table 4 shows the accuracy metrics of the ML models. The values presented are calculated for the daily energy predictions, while the success metrics described in Section 2.4.1.2 are based on the aggregated monthly error. Predicting the daily energy is a more difficult task than predicting the total monthly energy. The daily energy models significantly outperform the monthly targets, except for the baseline Seattle Office model, which has an error equal to worst-case acceptable values. However, given that the target metrics are for *monthly* energy and the models meet or exceed those values for *daily* energy, we can confidently say that the ML models are all able to reproduce and extend the original energy models' results with high fidelity.

Table 4. ML Model Accuracy Metrics

Site Name	Model	Energy Source	Adjusted r2 (daily)	CV RMSE (daily)	NMBE (daily)
Montana Office	Baseline	Electricity	0.9014	17.42%	1.27%
Montana Office	New VHE	Electricity	0.8948	21.16%	1.74%
Seattle Office	Baseline	Electricity	0.8399	25.14%	0.51%
Seattle Office	New VHE	Electricity	0.8196	19.09%	1.37%
Seattle Airport	Baseline	Electricity	0.8789	4.89%	0.17%
Seattle Airport	New VHE	Electricity	0.8405	6.25%	0.39%
Monument School	Baseline	Electricity	0.8215	16.26%	-0.62%
Monument School	New VHE	Electricity	0.8626	19.62%	-0.81%
Portland School	Baseline	Electricity	0.8988	20.80%	-0.44%
Portland School	New VHE	Electricity	0.9817	6.87%	-0.29%
Portland Government Office	Baseline	Electricity	0.9982	3.56%	-0.15%
Portland Government Office	Baseline	Gas	0.9924	10.54%	0.02%
Portland Government Office	New VHE	Electricity	0.9960	2.58%	0.20%
Portland Office	Baseline	Electricity	0.9999	0.59%	-0.01%
Portland Office	Baseline	Gas	0.9998	0.50%	-0.05%
Portland Office	New VHE	Electricity	0.9981	1.60%	0.04%

With the trained models, we were able to compare the modeled hypothetical code-minimum system to the VHE DOAS. Figure 4 shows the results of both daily energy models for the Portland School site along with the average daily temperature that was applied to each model.

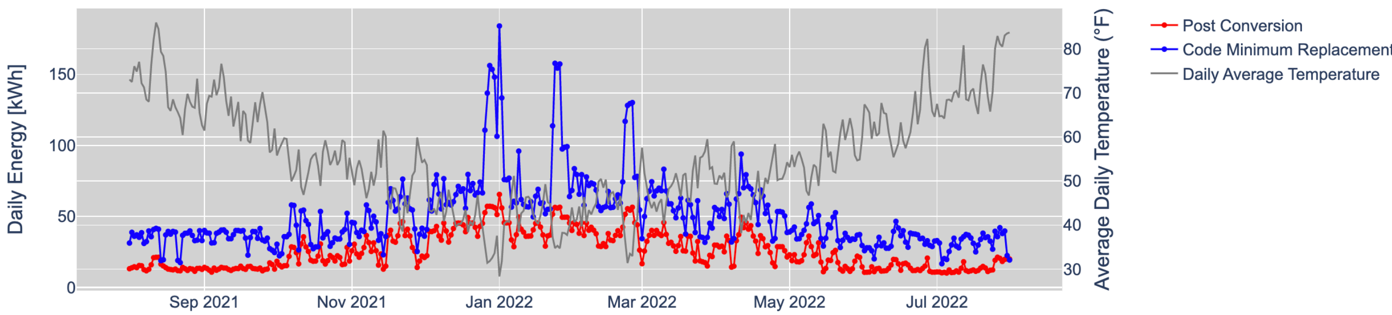

Figure 4. Modeled Daily Energy Consumption – Portland School

Table 5 provides the total annual energy consumption for both modeled systems for each site. In all cases, the VHE DOAS replacement is expected to save significant energy over the code-minimum baseline. These results also align well with the real-world whole-building utility billing savings shown in Section 2.4.1.1. The biggest deviation between the utility savings and the modeled energy savings is the Seattle Airport, which had a sustained savings of more than 75 percent compared to the previous system but a modeled savings of only 35 percent. The difference can be attributed to the poor efficiency of the original system, which had a substantial amount of simultaneous heating and cooling. It is also a good example of why the effort of modeling the expected difference between the VHE DOAS and the hypothetical code minimum; there is no limit to an existing system's inefficiency.

Table 5. Modeled Energy Savings Compared to Code-Minimum Replacement

Site	Code-Minimum Modeled Energy Use (kBTU)	VHE System Modeled Energy Use (kBTU)	Modeled Percent Savings
Montana Office	412,001	372,534	10%
Seattle Airport	1,954,250	1,265,348	35%
Monument School	401,997	269,691	33%
Portland School	62,932	32,391	49%
Portland Government Office	1,612,522	409,380	75%
Portland Office	763,721	93,216	88%

Figure 5 shows the comparison of the modeled whole-building energy savings of the original evaluation and the savings of this re-evaluation. The differences between the two model results can be attributed to the difference in heating demand resulting from the different weather being modeled. Despite these differences, the results are agreeable between the two evaluations as a whole.

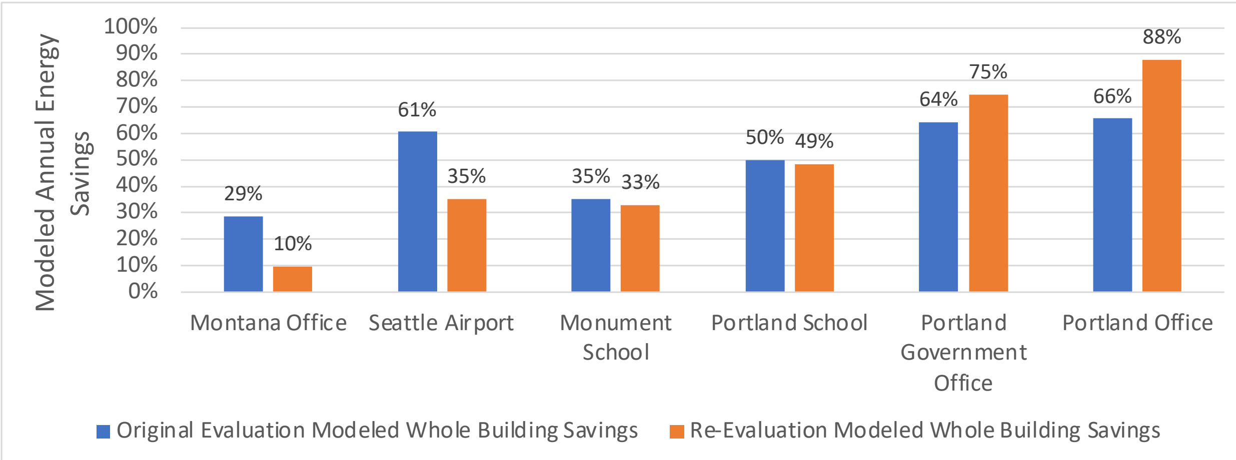

Figure 5. Comparison of Modeled Whole-Building Energy Savings Original Evaluation and Re-Evaluation

3.2 Indoor Air Quality Results

The set of data from the building occupant survey consisted of 44 responses from 5 different project sites with 95 percent of the responses coming from only 3 of the project sites. The main method of analysis was to compare the overall satisfaction levels as well as specific IEQ aspects, pre- and post-conversion. This requires responses from people that occupied the building both pre- and post-conversion; 55 percent (24/44) of the responses met that requirement. Table 6 shows a summary of the occupant survey results.

Table 6. Summary of Survey Responses

Site	Percent of Total Responses	Number of Responses Indicating Occupancy Both Pre- and Post-conversion
Montana Office	2% (1/44)	1
Seattle Office	39% (17/44)	1
Portland Government Office	21% (9/44)	6
Portland Office	36% (16/44)	15
Tarrytown	2% (1/44)	1

The questions asked in the survey focused on assessment of thermal comfort and satisfaction related to the IEQ parameters: temperature, air movement, noise from the HVAC system, and air quality. Figure 6 shows the responses to the thermal comfort question that compares thermal comfort pre- and post-conversion across all project sites, only showing responses from occupants who were in the building both pre- and post-conversion. Post-conversion, occupants tended to be less warm and more cool, shown by an 18 percent increase in reports of being cooler than neutral and 22 percent decrease in reports of being warmer than neutral.

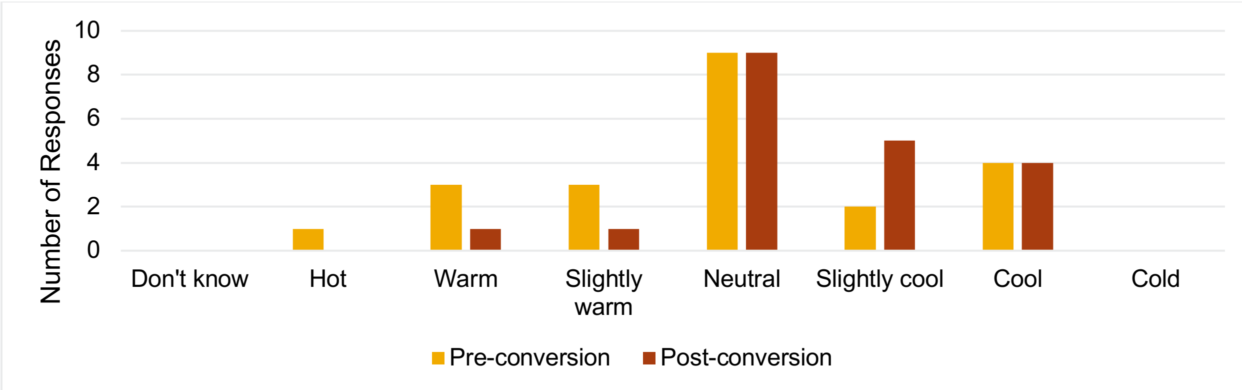

Figure 6. Occupant Thermal Comfort Results

Figure 7 shows a comparison similar to that shown in Figure 6, but in this case the question being asked is regarding thermal *satisfaction*. Similar figures were generated for questions regarding air movement, noise, and air quality and are presented in Appendix D. The main result from this figure is that post-conversion occupants expressed a 43 percent decrease in dissatisfaction.

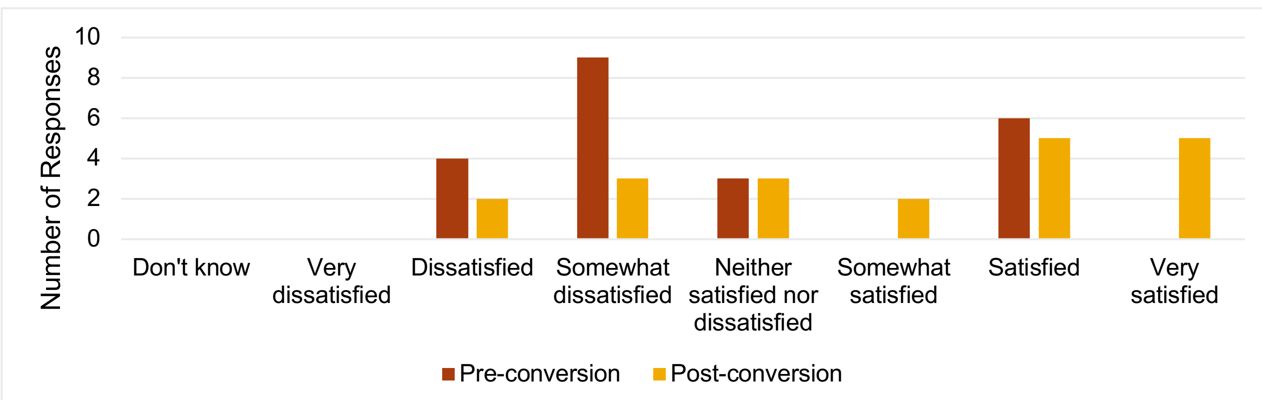

Figure 7. Occupant Thermal Satisfaction Results

Table 7 below shows a summary of how satisfaction and dissatisfaction changed across IEQ parameters for all project sites. A POSITIVE change indicates MORE reports post-conversion compared to pre-conversion. A NEGATIVE change indicates FEWER reports post-conversion compared to pre-conversion.

Table 7. Change In Satisfaction and Dissatisfaction Across IEQ Parameters

	Overall	**Temperature**	**Air Movement**	**Noise**	**Air Quality**
Percent change in SATISFACTION	+43.3	0	+43	+23.9	+5
Percent change in DISSATISFACTION	-29.7	-42.8	-28.8	+2.4	-41.7

In nearly all cases, satisfaction increased and dissatisfaction decreased post-conversion. Overall, occupants were 43 percent more satisfied and 30 percent less dissatisfied post-conversion compared to pre-conversion.

The quantitative analysis ability of the occupant survey data is limited given the small sample size and the uneven distribution of responses by project site (i.e., many responses from few sites). Due to this limitation, comparison between project sites is not done.

3.3 Building Operator Feedback Results

The satisfaction of building operators is an important element when determining the potential deployment success of a new technology. Often, new technologies can be viewed as overly complex or hard for existing facility staff to operate and maintain. Without the buy-in from O&M staff, well designed systems can quickly fall out of optimal operating conditions. Additionally, increased maintenance time and costs can negatively affect the financial benefits of system retrofits.

As was true for other parts of this study, the data for the operator questionnaire responses do not cover all the sites. Some of the sites did not respond to the questionnaire and others were not employed at the site before the new VHE system was installed. However, of the responses that were received, all but one indicated that the new system did not increase maintenance time or cost and, in some cases it, reduced both. Some of these reductions can be attributed to the new system completely replacing the old. Some sites were able to completely replace their old systems while others used the new system as a supplement to their old system. All respondents reported that it was easy to implement changes and adjustments in the system. All respondents reported being satisfied with the system with repots of being “very satisfied” and “5 out of 5 stars!” and positive comments such as “Overall, the system has made it easier to address building air quality.”

The small sample size of five responses prevents drawing conclusions for all buildings and VHE DOAS installations, but it does provide additional evidence that VHE DOAS conversions can reduce O&M costs in addition to achieving the energy savings and occupant comfort benefits.

4.0 Conclusion

The purpose of this re-evaluation was to confirm whether the benefits of VHE DOAS documented in the original NEEA analysis persisted over the subsequent years. Our results align strongly with the original evaluations.

The energy results were consistent with the original evaluation. The sites all saw similar or increased energy savings based on the utility billing data, averaging 48 percent whole site energy savings compared to the pre-conversion system. Energy modeling results showed that the savings for the new VHE DOAS compared to a hypothetical code baseline would be similar to those of the original evaluation. While the modeled savings were slightly different than their real-world counterparts, on average the modeled energy savings also showed a 48 percent reduction compared to the baseline.

The non-energy benefits described in the original evaluation were also validated in this study. An occupant satisfaction survey was created and distributed to current building occupants; it asked questions regarding IEQ parameters such as thermal comfort, thermal satisfaction, air movement satisfaction, acoustic satisfaction, air quality/freshness satisfaction, and perception of maintenance activities. The results of the survey showed that overall and across IEQ parameters occupants were 43 percent MORE satisfied with the post-conversion system compared to the pre-conversion system. Additionally, the O&M staff contacted for this study indicated that the system conversion either reduced or did not affect maintenance costs.

The results of this study further validate the findings documented by NEEA and IMT in the original evaluation: VHE DOAS retrofits offer a significant opportunity to save energy, reduce operating costs, and increase occupant comfort.

Despite the well documented benefits of these types of systems, they have yet to see a large growth in market share. NEEA (2019, 2022) has done extensive work to characterize the market barriers that exist for VHE DOASs. They found that the primary drivers limiting their adoption are the high first cost of the systems and a lack of knowledge among key decision-makers.

Both NEEA and IMT have also highlighted the need for improved rating systems for ventilating equipment, particularly the energy recovery components. The current standards generally consider only standard conditions (the temperatures and humidity levels at which the devices are tested), but in practice, the equipment may spend only a few hours a year at those conditions. The performance of the energy recovery equipment can vary dramatically throughout the range of conditions that the equipment is likely to experience. Having a more complete testing standard that covers a wider range of operating conditions would help engineers, contractors, and building owners make better-informed decisions about the ventilation system.

Finally, many interested parties are working on education and outreach for specific components of the VHE DOAS concept (e.g., groups focused on VRF and/or heat pumps, and others focused on DOASs). All of the parties would benefit from high-level coordination to assure consistent messaging, prevent duplication of work, and expand their sphere of influence.

5.0 References

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Appendix A – Extended Site Descriptions

Table A.1 through Table A.8 present a summary of each site's building characteristics; heating, ventilation, and air-conditioning system; and energy use.

Table A.1. Montana Office

Characteristic	Value
Site Name	Montana Office
Occupant	Electric Co-Op
State	Montana
Climate Zone	6B
Conversion Date	August 2016
Floor Area (ft^2)	5,735
Building Description	Single-story 1960s-vintage building with offices, storage space, and four garage bays.
Occupancy	Monday-Friday, 7 a.m.–5 p.m.; some after hours
Envelope	Windows: U-0.5 office, U-0.9 storage/garage Walls: R-10 office, R-7 storage/garage Roof: R-8 office, R-35 storage/garage
Pre-Conversion HVAC System	160 kW two-circuit electric boiler served hydronic unit heaters in the storage/garage space, and wall-mounted perimeter radiator units served the office spaces. The hydronic system did not have separate zones, so the entire building heated up when the system was on. A 6-ton heat pump rooftop unit (RTU) provided cooling and ventilation to the office space. Two swamp coolers were used for cooling and ventilation in the storage/garage space. There was a 0.75-ton ductless heat pump for a small computer server room. One manual thermostat served the office space and one manual thermostat served the storage/garage space. Electric boiler: (1) Weil-McLain CEW-80, 546 kBtu/hr heating capacity, 2 zones Swamp coolers: (2) Champion 7500 SD, unknown cooling capacity, 1 zone Heat Pump RTU: (1) Lennox CHP16-953-3Y, 6-ton heating and cooling capacity, 1 zone Server Room Heat Pump: (1) Fujitsu AOU9RLFW, 9 kBtu/hr cooling capacity, 12 kBtu/hr heating capacity, 1 zone
Post-Conversion HVAC System	Two multi-zone heat pump systems and a very high efficiency heat recovery ventilator (VHE HRV) system. The existing electric boiler-fed hydronic system was placed in back-up mode to supplement the heat pumps under the most extreme ambient conditions. The office space has 7 indoor units with their own wall controllers and the storage/garage space is served by two air-handling units (AHUs) managed by a single wall controller. Heat Pump Units: (2) Mitsubishi MXZ48-8C, 4.5-ton each cooling capacity, 4.75-ton each heating capacity, 8 zones Packaged HRV: (1) Ventacity VS1000RT, 1,025 cfm, 2 zones
Energy Savings Reported in Original Study	Pre-conversion actual /post-conversion actual EUI (kBtu/ft^2/yr): Total: 102.2/70.0 HVAC: 66.5/34.3 Pre-conversion code-minimum/post-conversion modeled EUI (kBtu/ft^2/yr): Total: 98.0/70.0 HVAC: 62.3/34.3 Fans: 12.8/3.2 Heating: 46.2/28.8

Characteristic	Value
	Cooling: 3.3/2.3

Table A.2. Seattle Office

Characteristic	Value
Site Name	Seattle Office
Occupant	Engineering Office
State	Washington
Climate Zone	4C
Conversion Date	September 2016
Floor Area (ft^2)	6,100
Building Description	Third floor of 3.5-story mixed-use historic building including an open office space, conference rooms, lunchroom, and server room.
Occupancy	Monday-Friday, 7 a.m.–10 p.m.
Envelope	Walls: R-5 Roof: R-11 Windows: R-1.7
Pre-Conversion HVAC System	Electric RTU w/ electric-resistance terminal heat. The pre-conversion RTU served the entire building and had a cooling capacity of 35 tons. Only the third floor was retrofitted; the rest of the building is still served by the original RTU. Electric RTU w/ electric-resistance terminal heat: (1) Carrier 50AK-035CR-511HH, 14 tons of cooling capacity, 16.4 tons of heating capacity, 4 zones
Post-Conversion HVAC System	The heating and cooling system is a VRF with 12 ductless indoor units. The ventilation system is an HRV. VRF: Mitsubishi PURY-P168TLMU-A, 14 tons of cooling capacity, 15.7 tons of heating capacity, 12 zones Packaged HRVs: (1) Ventacity VS1000RT, 1,025 cfm capacity, 1 zone
Energy Savings Reported in Original Study	Pre-conversion/post-conversion modeled EUI (kBtu/ft^2/yr): Total: 51.3/29.7 HVAC: 31.2/9.6 Fans: 2.8/0.9 Heating: 27.1/7.9 Cooling: 1.2/0.8

Table A.3. Seattle Airport

Characteristic	Value
Site Name	Seattle Airport
Occupant	County Airport
State	Washington
Climate Zone	4C
Conversion Date	April 2017
Floor Area (ft^2)	25,200
Building Description	2-story airport terminal building built in the 1930s. Approximately 4,000 ft^2 of the building is single-story. The majority of the building houses airport administration, security, and

Characteristic	Value
	customs functions. The space also includes passenger- and baggage-handling facilities, a small deli, and a small basement with controls for the airfield lighting system. Electrical, lighting, and envelope upgrades were made in 2002.
Occupancy	Monday-Friday, 8 a.m.–5 p.m.
Envelope	Walls: R-3 Roof: R-12.7 Windows: U-0.9
Pre-Conversion HVAC System	The 2-story part of the building was served by 2 RTUs installed in 1996, each with an estimated cooling and heating capacity of 40 tons. The 4,000 ft^2 single-story part of the building was served by an RTU installed in 2002 with a cooling capacity of 15 tons and a heating capacity of 12 tons. Two 5 kW and one 10 kW electric-resistance heaters served the passenger vestibule and baggage-handling areas. The system had significant simultaneous heating and cooling inherent in the design of dual-deck RTUs. Full pre-conversion system details are not available; RTU capacity is estimated. Gas-electric dual-deck RTUs: (2) unknown model w/ ~40 tons of cooling capacity, (1) unknown model w/ ~15 tons of cooling capacity, unknown heating capacity, 15 zones Electric-resistance units: (2) unknown model w/ 1.4 tons of heating capacity, (1) unknown model w/ 2.8 tons of heating capacity, unknown cooling capacity, 3 zones
Post-Conversion HVAC System	System description: 4 VRF outdoor units and 3 packaged HRVs. VRF Outdoor Units: (2) Mitsubishi PURY-P96YLMU-A, 8-ton cooling capacity, 9-ton heating capacity; (1) Mitsubishi PURY-P120YLMU-A, 10-ton cooling capacity, 13.25-ton heating capacity; (1) Mitsubishi PURY-P72YLMU-A, 6-ton cooling capacity, 6.5-ton heating capacity; 37 zones Packaged HRVs: (3) Ventacity VS1000RT 1,025 cfm each, 4 zones
Energy Savings Reported in Original Study	Pre-conversion actual /post-conversion actual EUI (kBtu/ft^2/yr): Total: 175.4/53.2 HVAC: 140.7/18.5 Pre-conversion code-minimum/post-conversion modeled EUI (kBtu/ft^2/yr): Total: 122.0/48.1 HVAC: 87.3/13.3 Fans: 33.9/2.8 Heating: 45.5/8.1 Cooling: 7.9/2.4

Table A.4. Monument School

Characteristic	Value
Site Name	Monument School
Occupant	Rural Elementary School
State	Oregon
Climate Zone	5B
Conversion Date	September 2020
Floor Area (ft^2)	7,200
Building Description	1965 single-story school with five classrooms, two restrooms, speech therapy room, and three small storage rooms.
Occupancy	Monday-Friday, 7 a.m.–4p.m.
Envelope	Walls: R-11

Characteristic	Value
	Roof: R-19 Windows: R-0.9
Pre-Conversion HVAC System	The school was served by 5 unitary heat pumps supplemented by 1–3 electric-resistance space heaters per classroom. The ventilation systems consisted of manual, uncontrolled, unconditioned exhaust fans and operable windows. Packaged heat pump: (5) Goodman PH-030-1A, 12.5 tons of cooling capacity, 12.5 tons of heating capacity, 5 zones
Post-Conversion HVAC System	The post-conversion HVAC system consists of 5 2-ton mini-split heat pumps serving the classroom and a 1.5-ton ductless mini-split heat pump serving the speech therapy room. Ventilation uses a packaged HRV. Ductless heat pumps: (5) Bryant 38MAQR24, (1) Bryant 38MAQR18, 11.5 tons cooling of capacity, 12 tons of heating capacity, 6 zones HRV: Ventacity VS1000RTh, 1,025 cfm, 1 zone
Energy Savings Reported in Original Study	Pre-conversion/post-conversion modeled EUI (kBtu/ft^2/yr): Total: 52.7/34.2 HVAC: 37.0/18.4 Fans: 8.6/1.7 Heating: 17.5/14.4 Cooling: 10.9/2.3

Table A.5. Portland School

Characteristic	Value
Site Name	Portland School
Occupant	Urban Preschool
State	Oregon
Climate Zone	4C
Conversion Date	October 2020
Floor Area (ft^2)	2,900
Building Description	The Kishalay building includes two classrooms, a small office, and a teacher’s lounge.
Occupancy	Monday-Friday, 7 a.m.–5 p.m. Saturday-Sunday, 9 a.m.–3 p.m.
Envelope	Windows: U-0.21 Walls: R-22 Roof: R-58
Pre-Conversion HVAC System	The pre-conversion HVAC system was a constant volume 5-ton packaged heat pump rooftop unit. Packaged heat pump: (1) Johnson Controls J05XN, 5 tons of cooling capacity, 4 tons of heating capacity, 1 zone
Post-Conversion HVAC System	The post-conversion HVAC system consists of a 1.5-ton ductless heat pump (DHP) serving each of the two classrooms and 2-ton ducted mini-split serving the office and teacher’s lounge. Ductless heat pumps and ducted mini-split: (2) LG LS180HSV5, (1) LG LH247HV, 5 tons of cooling capacity, 6 tons of heating capacity, 3 zones Packaged HRV: Ventacity VS1000RT, 1,025 cfm, 1 zone

Characteristic	Value
Energy Savings Reported in Original Study	Pre-conversion/post-conversion modeled EUI (kBtu/ft^2/yr): Total: 25.7/12.9 HVAC: 22.1/9.3 Fans: 7.8/0.8 Heating: 13.8/8.3 Cooling: 0.5/0.2 DHW: 1.7/1.7 Other: 1.9/1.9

Table A.6. Portland Government Office

Characteristic	Value
Site Name	Portland Government Office
Occupant	Urban Government Building
State	Oregon
Climate Zone	4C
Conversion Date	August 2020
Floor Area (ft^2)	20,000
Building Description	1956 vintage building that was built as a school and was converted into an office space. The building is metal-framed with a brick exterior.
Occupancy	Heating/cooling: 24/7 Ventilation: M-F, 6 a.m.–6 p.m.
Envelope	Walls: R-14 Roof: R-31 Windows: R-1.1
Pre-Conversion HVAC System	A natural gas steam boiler originally served the entire building and there was no air conditioning. Ductless heat pumps were added in 2018-2019 to provide primary heating and cooling while the boiler continued to condition ventilation air. Heat pump units: (9) Daikin RMXS48LVJU, 36 tons of cooling capacity, 40.5 tons of heating capacity, 9 zones Natural gas steam boiler: (1) Gabriel Boiler, 3,100 MBH of heating capacity, 1 zone Ventilation system: (2) fixed-speed 5-hp fans (one supply, one exhaust), 7,253 cfm actual/12,690 cfm max, 1 zone
Post-Conversion HVAC System	The post-conversion system uses the pre-conversion heat pump units. With the new HRV, the natural gas boiler is no longer needed. Heat pump units: (9) Daikin RMXS48LVJU, 36 tons of cooling capacity, 40.5 tons of heating capacity, 9 zones Packaged HRV: (1) Ventacity VS3000, 1,500 cfm design/12,690 max, 1 zone
Energy Savings Reported in Original Study	Pre-conversion/post-conversion modeled EUI (kBtu/ft^2/yr): Total: 67.5/24.2 HVAC: 55.0/11.7 Fans: 3.0/2.2 Heating: 44.2/8.5 Cooling: 1.5/1.0 Pumps: 6.4/0.0 Other: 12.5/12.5

Table A.7. Portland Office

Characteristic	Value
Site Name	Portland Office
Occupant	Engineering Office
State	Oregon
Climate Zone	4C
Conversion Date	April 2021
Floor Area (ft^2)	11,500
Building Description	Originally built as a warehouse, the building was renovated in 2014 to include six private office suites, a central common workspace, and a public café. Each suite received its own HVAC system. The total conditioned floor area of the building is 11,500 ft^2 , but this study only analyzes the largest suite (Suite 1) and the common space/café (7,569 ft^2). Suite 1 includes a large open office area, a second-story mezzanine open to the common space and the first floor of the suite, and two private offices.
Occupancy	Heating/cooling: Monday-Sunday, 7 a.m. – 6 p.m. Ventilation: Monday-Friday, 5 a.m. – 6 p.m.
Envelope	Windows: R-2.2 Walls: R-1.8 Roof: R-36
Pre-Conversion HVAC System	The pre-conversion system consisted of RTUs with gas heat and electric direct expansion (DX) cooling. The RTUs were controlled by thermostats in Suite 1, but they indirectly conditioned and ventilated the café/common area. Packaged single-zone rooftop units (gas heat): (2) Carrier 48TCED09, 17 tons of cooling capacity, 25 tons (296 MBH) of heating capacity, 1 zone Split-system heat pump: (1) Carrier FX4DNF037, 3 tons of cooling capacity, 1 zone
Post-Conversion HVAC System	The post-conversion system consists of a VRF air-source heat pump with seven indoor ductless fan coil units and two HRVs. VRF heat pump: (1) LG ARUM121BTE5, 10 tons of cooling capacity, 11 tons (135 MBH) of heating capacity, 7 zones HRVs: (2) Ventacity VS1000RTh, 1,500 cfm (design) 2,100 cfm (max), 2 zones
Energy Savings Reported in Original Study	Pre-conversion/post-conversion modeled EUI (kBtu/ft^2/yr): Total: 62.3/13.3 HVAC: 58.2/9.2 Fans: 4.2/1.4 Heating: 52.7/7.0 Cooling: 1.3/0.8 Other: 4.1/4.1

Table A.8. Tarrytown Office

Characteristic	Value
Site Name	Tarrytown Office
Occupant	Property Management Company
State	New York
Climate Zone	4A
Conversion Date	September 2019
Floor Area (ft^2)	70,926

Characteristic	Value
Building Description	Office
Occupancy	Unknown
Envelope	Unknown
Pre-Conversion HVAC System	Gas heat RTUs
Post-Conversion HVAC System	VRF and ERV
Energy Savings Reported in Original Study	Pre-conversion/post-conversion modeled EUI (kBtu/ft^2/yr): Total: 148/50

Appendix B – Extended Energy Results

Figure B.1–Figure B.16 show EUI by time period and fuel type for each site. These figures show the degree of energy savings, persistence of energy savings, and the impact of fuel switching for sites with natural gas.

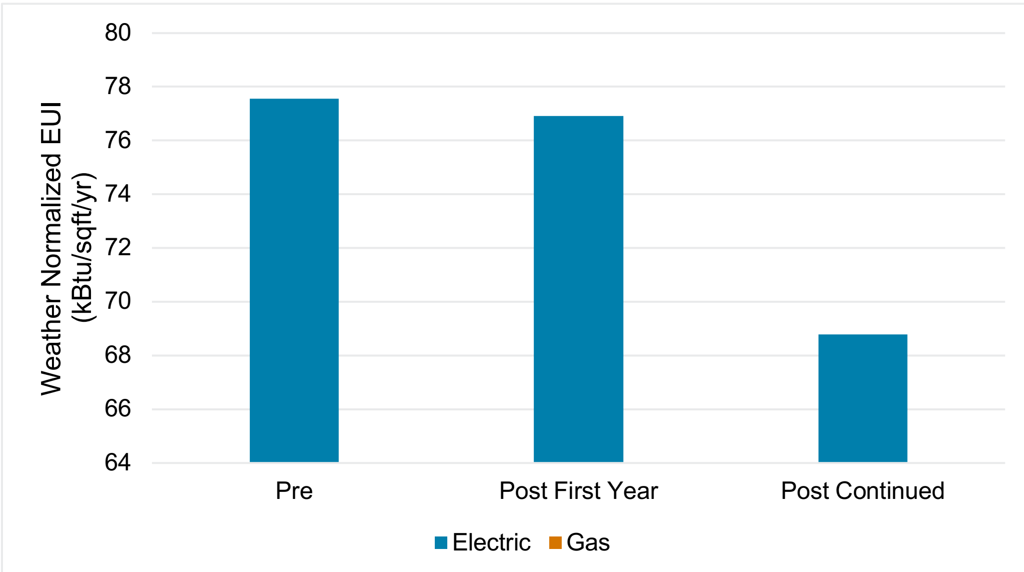


Figure B.1. Montana Office Weather-Normalized Average EUI by Time Period and Fuel Type

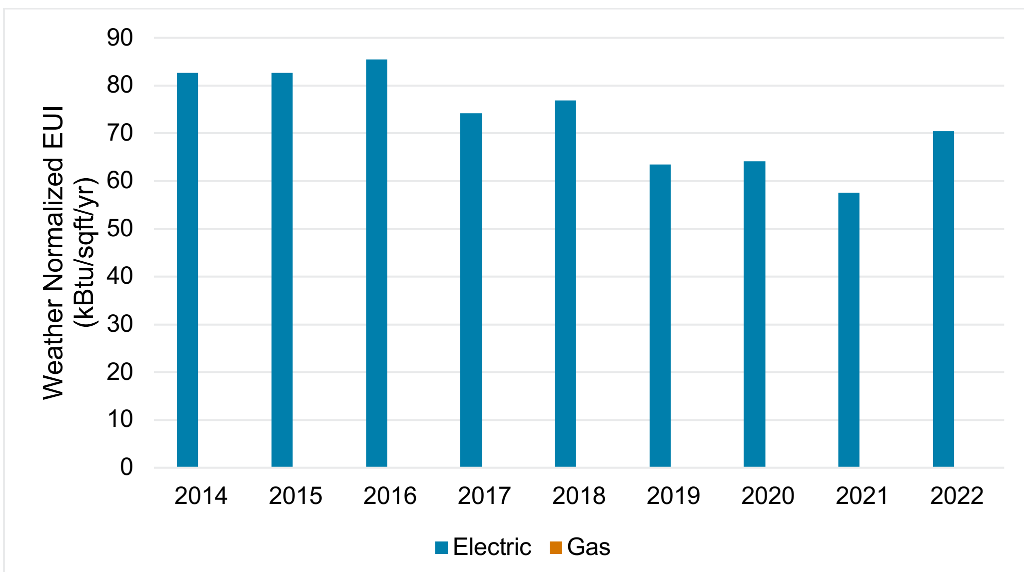


Figure B.2. Montana Office Weather-Normalized Annual EUI by Fuel Type

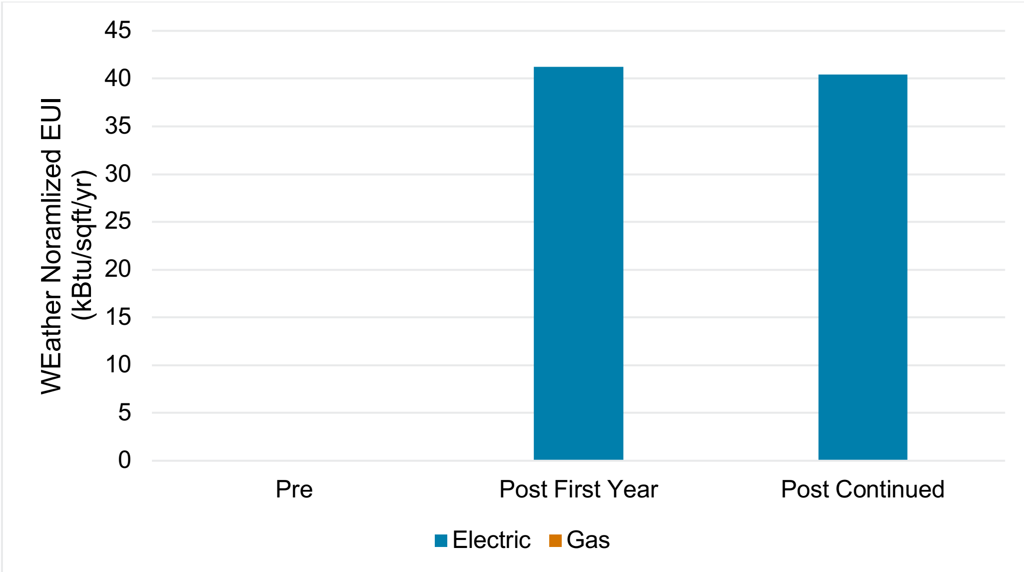


Figure B.3. Seattle Office Weather-Normalized Average EUI by Time Period and Fuel Type

Pre-conversion data are not available for the Seattle Office, which was not occupied by the current tenant pre-conversion.

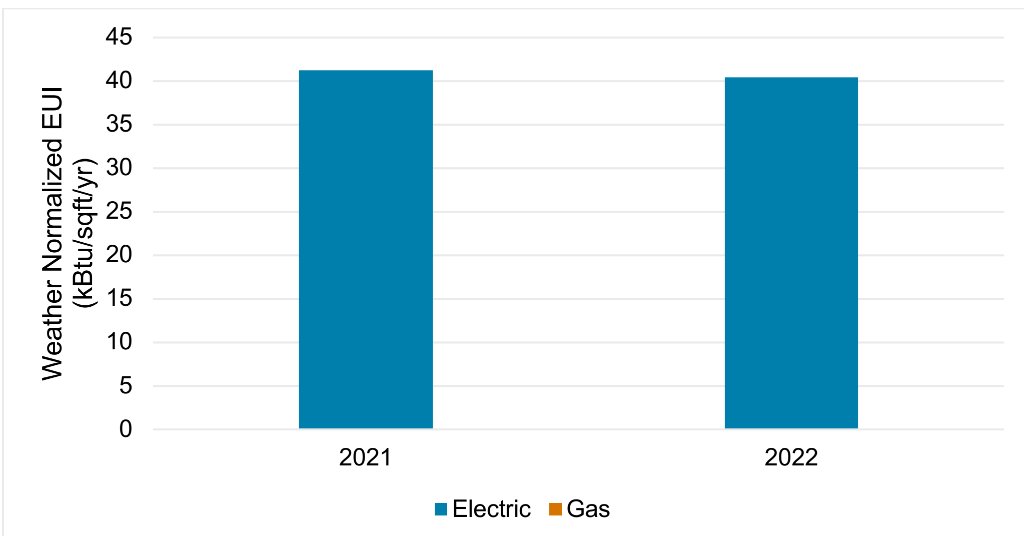


Figure B.4. Seattle Office Weather-Normalized Annual EUI by Fuel Type

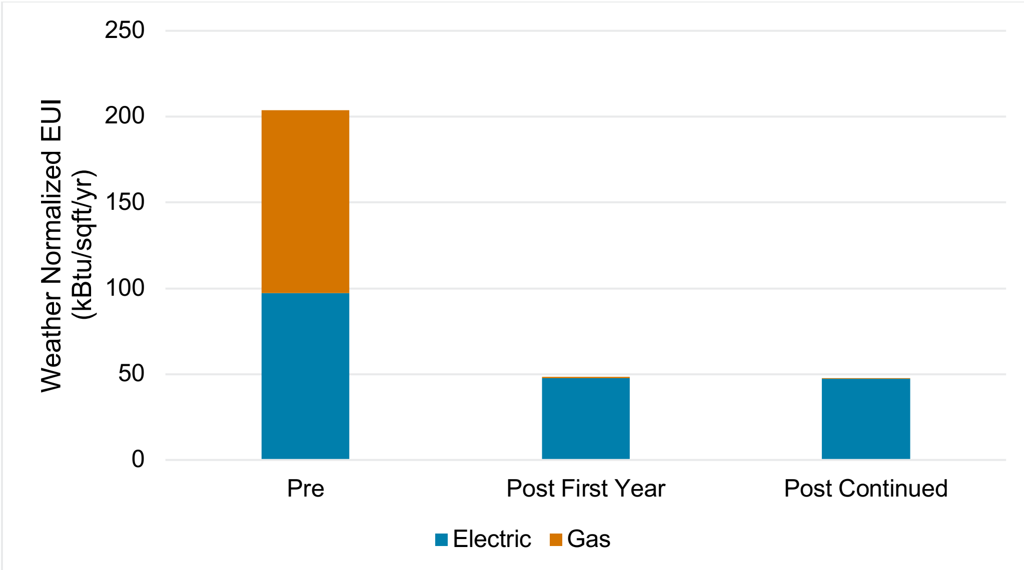


Figure B.5. Seattle Airport Weather-Normalized Average EUI by Time Period and Fuel Type

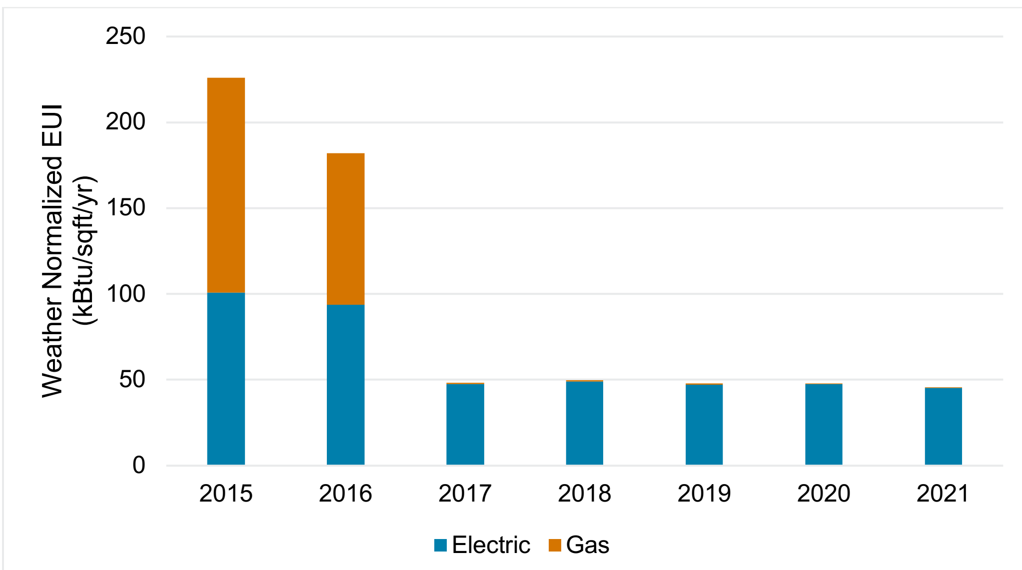


Figure B.6. Seattle Airport Weather-Normalized Annual EUI by Fuel Type

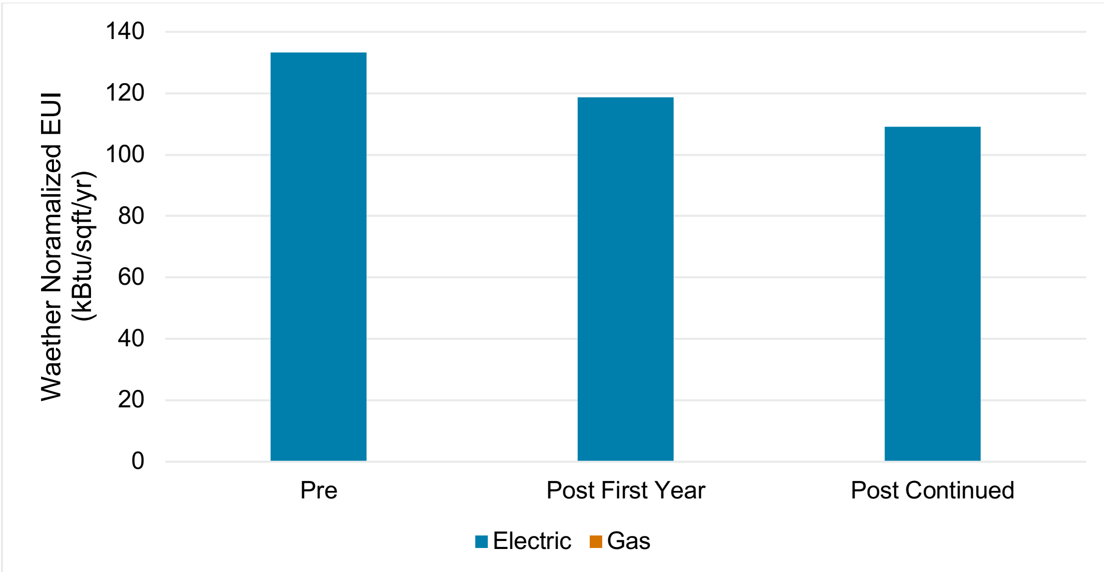


Figure B.7. Monument School Weather-Normalized Average EUI by Time Period and Fuel Type

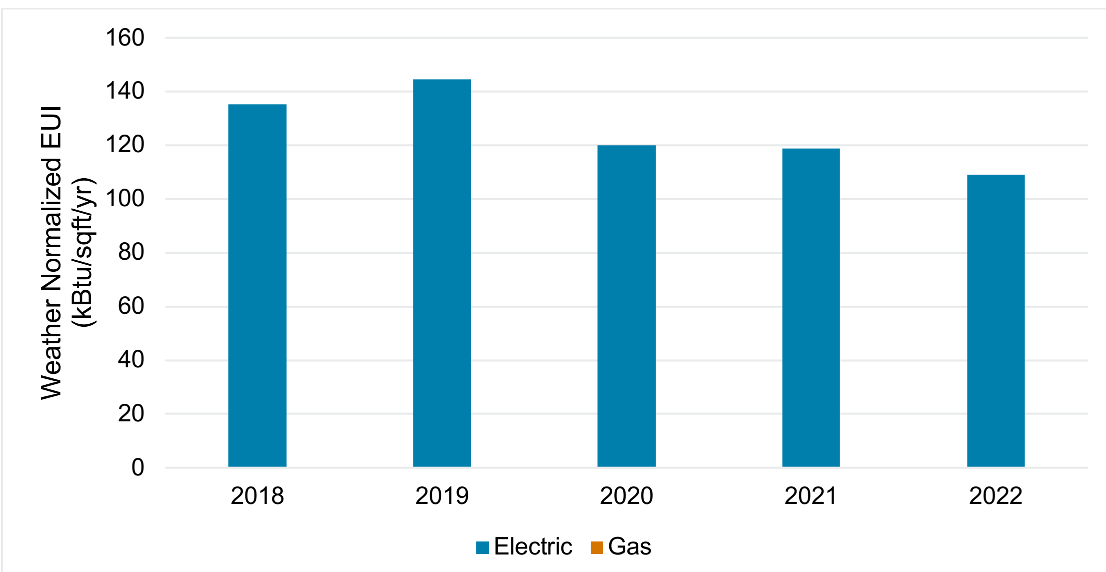


Figure B.8. Monument School Weather-Normalized Annual EUI by Fuel Type

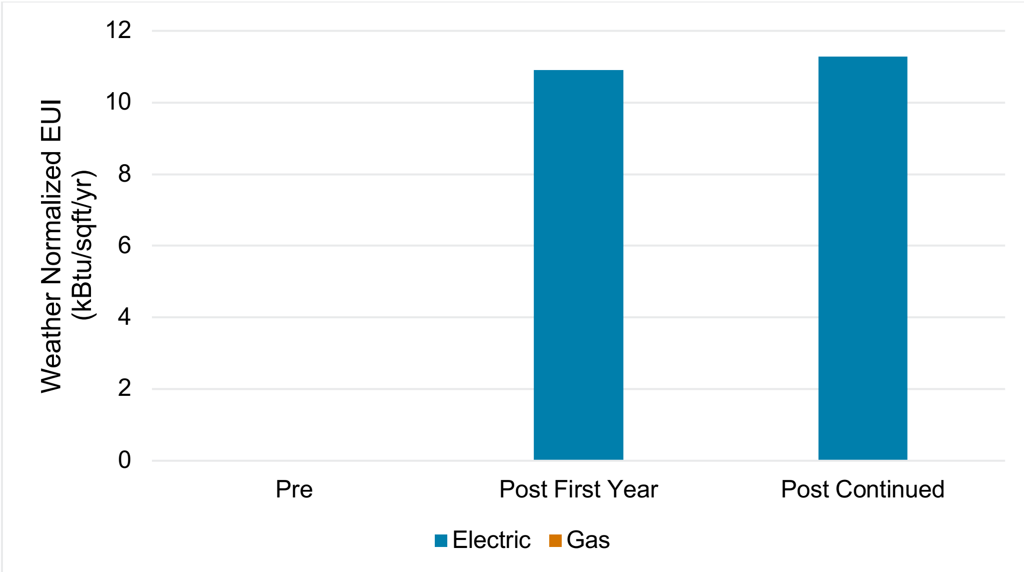


Figure B.9. Portland School Weather-Normalized Average EUI by Time Period and Fuel Type

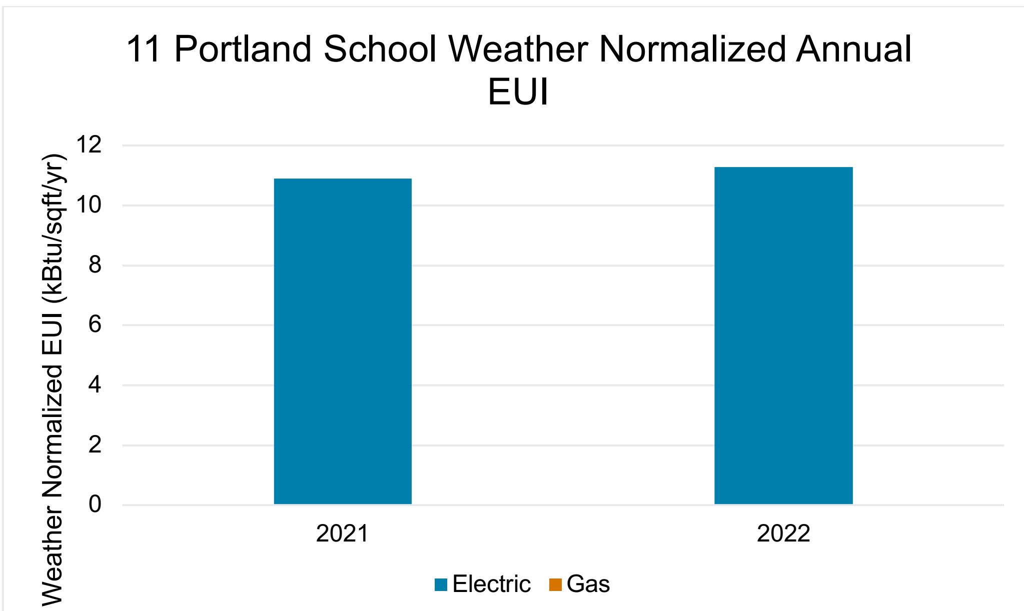


Figure B.10. Portland School Weather-Normalized Annual EUI by Fuel Type

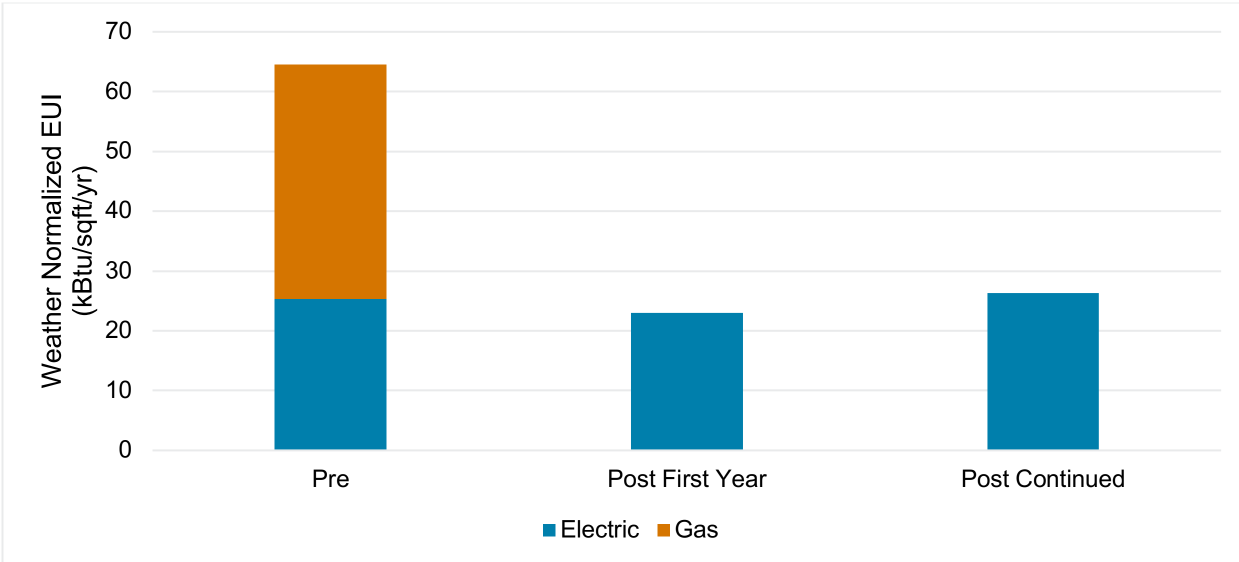


Figure B.11. Portland Government Office Weather-Normalized Average EUI by Time Period and Fuel Type

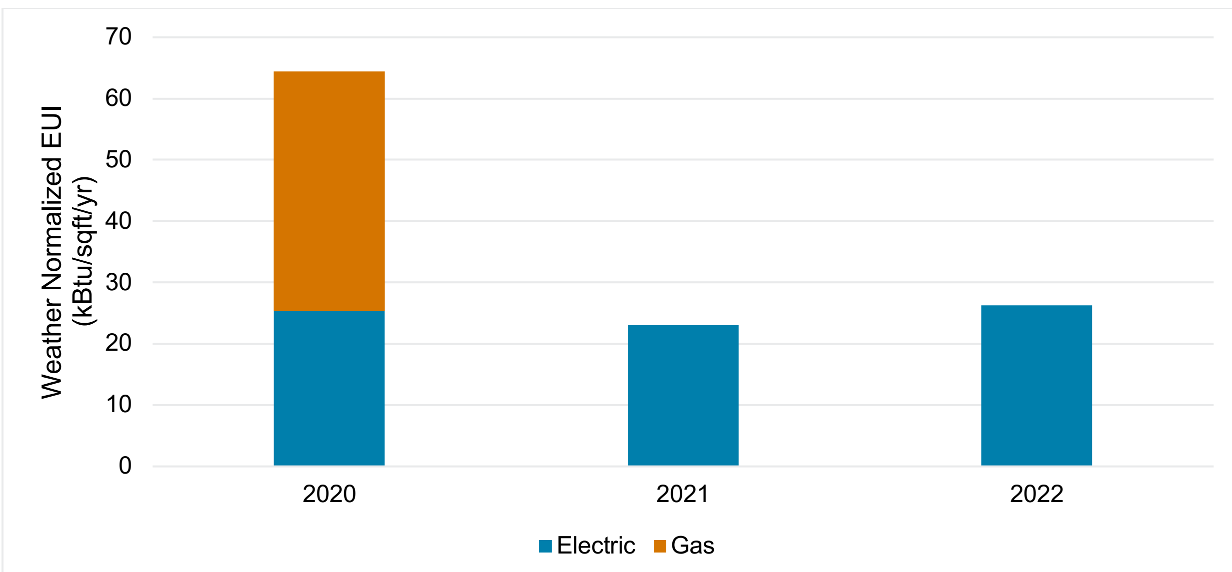


Figure B.12. Portland Government Office Weather-Normalized Annual EUI by Fuel Type

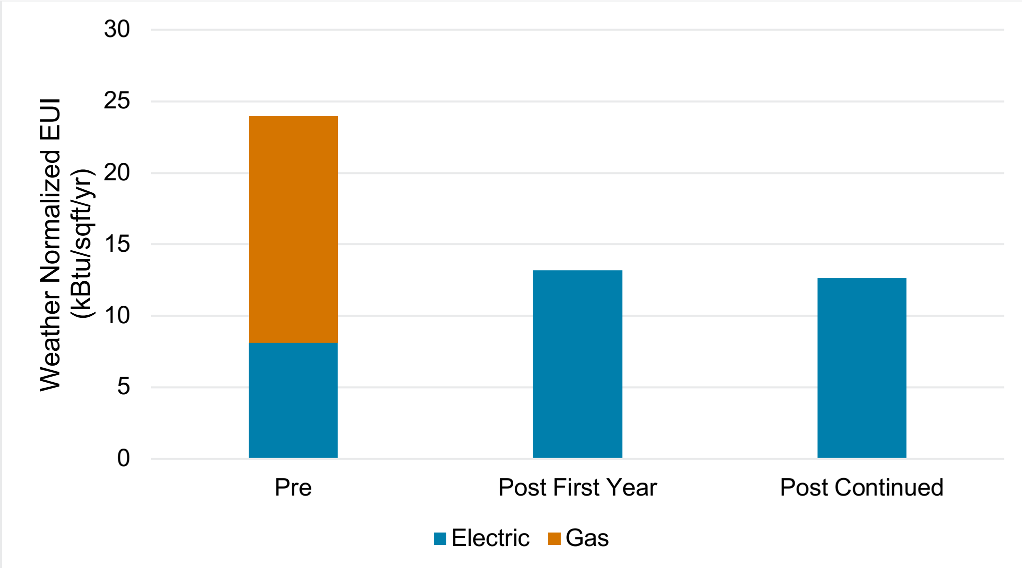


Figure B.13. Portland Office Weather-Normalized Average EUI by Time Period and Fuel Type

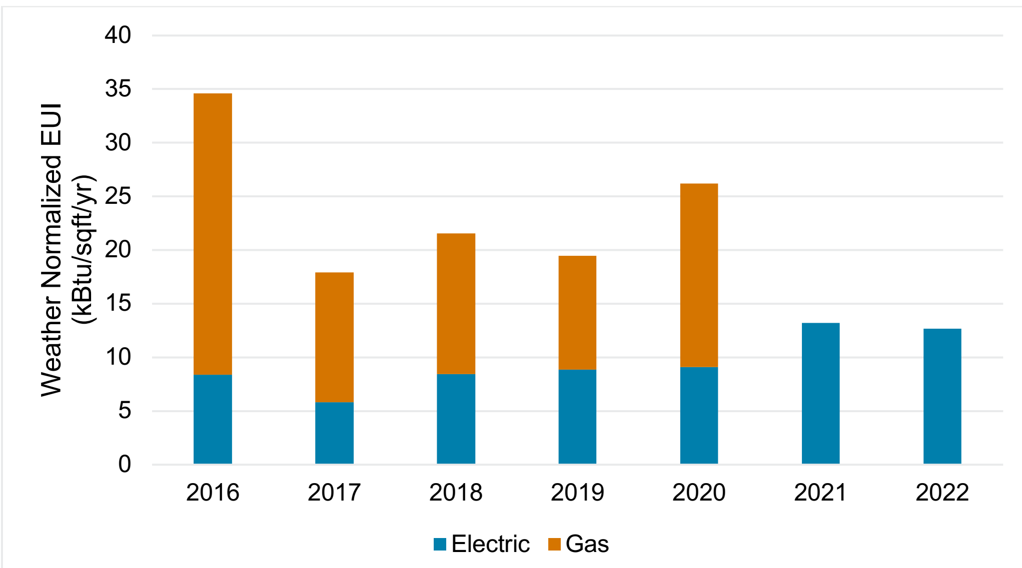


Figure B.14. Portland Office Weather-Normalized Annual EUI by Fuel Type

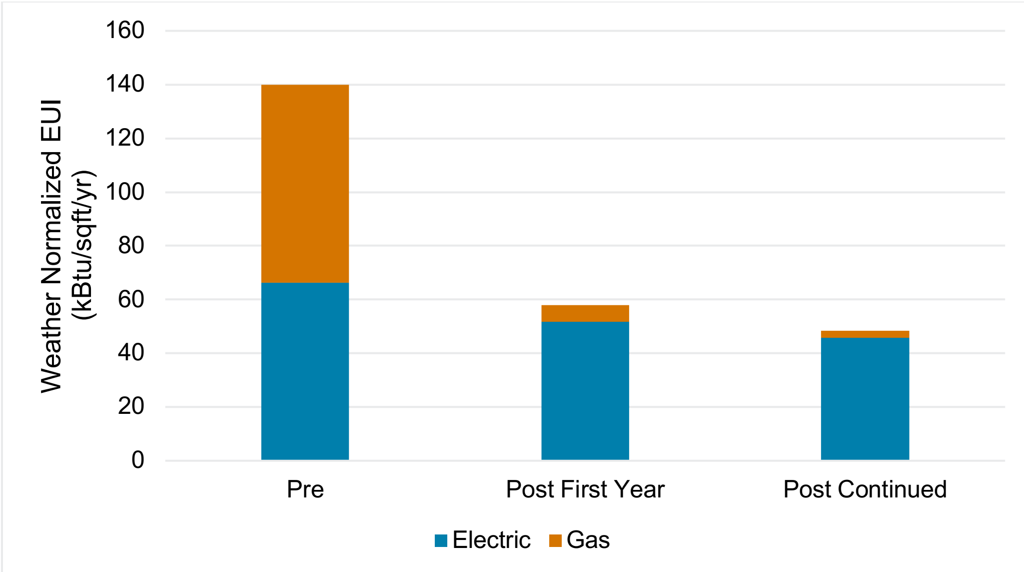


Figure B.15. Tarrytown Office Weather-Normalized Average EUI by Time Period and Fuel Type

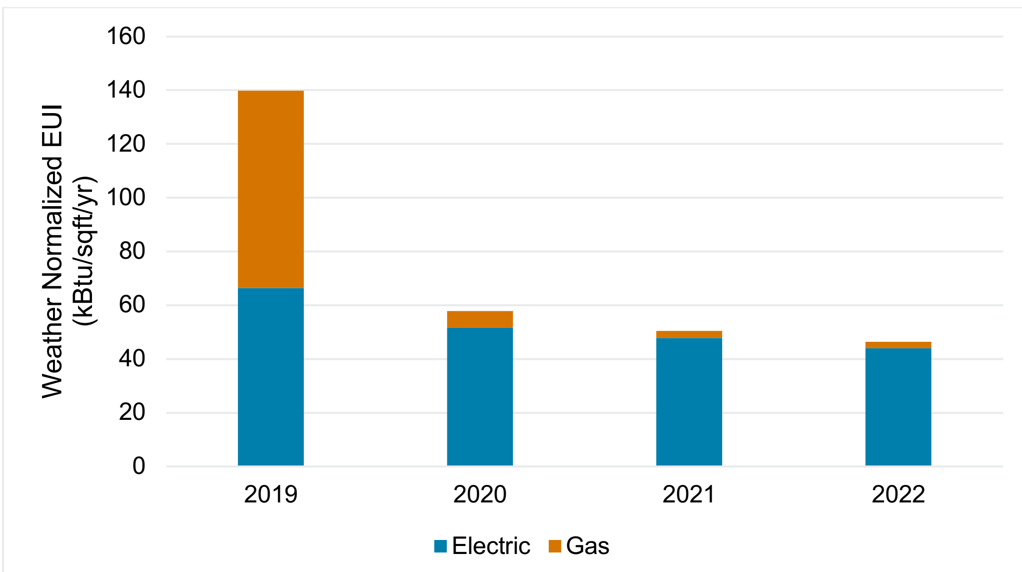


Figure B.16. Tarrytown Office Weather-Normalized Annual EUI by Fuel Type

Appendix C – Building Occupant HVAC Satisfaction Survey

Building Occupant HVAC Satisfaction Survey

Project Title: Very High Efficiency (VHE) Heating Ventilating and Air-Conditioning (HVAC) 3rd Party Evaluation

Principal Investigator: Tim Yoder

You are being asked to be a volunteer in a research study.

What is this study about?
The purpose of this research is to see if your building's heating ventilating and air-condition (HVAC) system makes your building a comfortable place to work. The research will also be looking at the energy savings of the system compared to the old HVAC system.

What will we ask you to do?
This survey will ask questions about how you rate the comfort of your building. For example, we will ask if you think the space is usually too hot or too cold. It will take about 5 minutes to fill out the survey. You may skip any questions that you do not want to answer.

What are the risks of being in this study?
There are no anticipated risks to participating in this study.

Will being in this study help me in any way?
You are not likely to personally benefit in any way from joining this study. But it may help people in the future. What we learn may help in the following ways:

- **Validate performance of high efficiency HVAC system**
- **Reduce greenhouse gas emissions**

Will I be paid?
No. You will not be paid for being in this study.

How will my information be kept confidential?
All efforts will be made to keep your responses confidential, but total confidentially cannot be guaranteed.

We will use Survey Monkey to collect and forward your anonymous responses to us. We will not receive any information that can identify you or other participants. We will download your responses to a secure file that will be stored on a PNNL password protected computer. There is no plan to delete the survey data.

Your anonymous information will only be used in this study.

We might be required to share the information we collect from you with the Pacific Northwest National Laboratory Institutional Review Board (a committee that reviews and approves human subject research studies), other federal regulatory agencies, or the sponsor of the study. If this happens, the information would only be used to find out if we ran this study properly and protected your rights in the study.

Taking part is voluntary
Your participation in this study is voluntary. You do not have to be in this study if you don't want to be. You have the right to change your mind and leave the survey at any time. You may skip any question you do not wish to answer.

Who can answer my questions about the study?
If you have any questions about the study, contact the Tim Yoder, principal investigator, at (509) 375-3638, or by email at tim.yoder@pnnl.gov. If you have any questions about your rights as a research participant or other questions, you may contact Susan Varnum at 509-371-7299 (susan.varnum@pnnl.gov) in Human Research Protection Program/Institutional Review Board.
Please print out this consent form if you would like a copy of it for your files.

Consent
If you have read the information contained in this document, and if you consent to participate in this research study and to the terms above, please

* 1. Were you an occupant of the building prior to DATE?

- Yes
- No

* 2. In general, what was your ***thermal comfort*** while in the building prior to DATE?

- Hot
- Warm
- Slightly warm
- Neutral
- Slightly cool
- Cool
- Cold
- Don't know

* 3. In general, how satisfied were you with the ***temperature*** in the building prior to DATE?

- Very dissatisfied
- Dissatisfied
- Somewhat dissatisfied
- Neither satisfied nor dissatisfied
- Somewhat satisfied
- Satisfied
- Very satisfied
- Don't know

* 4. What was the source of your dissatisfaction related to the ***temperature*** prior to DATE? Select all that apply.

- [ ] Air movement too high
- [ ] Air movement too low
- [ ] Incoming sun
- [ ] Drafts from windows
- [ ] Drafts from vents
- [ ] Hot/cold surrounding surfaces (floor, ceiling, walls, or windows)
- [ ] Heating/cooling system does not respond quickly enough to thermostat
- [ ] Other (please specify)
- [ ] Don't know

5. If you'd like to elaborate on your selection, please do so here:

* 6. In general, how satisfied were you with the ***air movement*** in the building prior to DATE?

- ◯ Very dissatisfied
- ◯ Dissatisfied
- ◯ Somewhat dissatisfied
- ◯ Neither satisfied nor dissatisfied
- ◯ Somewhat satisfied
- ◯ Satisfied
- ◯ Very satisfied
- ◯ Don't know

* 7. What was the source of your dissatisfaction related to the ***air movement*** prior to DATE? Select all that apply.

- ☐ Stuffy (not enough air movement)
- ☐ Drafty (too much air movement)
- ☐ Too dry
- ☐ Too humid
- ☐ Other (please specify)
- ☐ Don't know

8. If you'd like to elaborate on your selection, please do so here:

* 9. In general, how satisfied were you with the level of ***noise*** from the heating, ventilation, and cooling system prior to DATE?

- ◯ Very dissatisfied
- ◯ Dissatisfied
- ◯ Somewhat dissatisfied
- ◯ Neither satisfied nor dissatisfied
- ◯ Somewhat satisfied
- ◯ Satisfied
- ◯ Very satisfied
- ◯ Don't know

* 10. What was the source of your dissatisfaction related to the heating, ventilation, and cooling system ***noise*** prior to DATE? Select all that apply.

- ☐ Loud operation
- ☐ High frequency noises
- ☐ Low frequency noises
- ☐ Motor noises
- ☐ Hissing/air movement noises
- ☐ Other (please specify)
- ☐ Don't know

11. If you'd like to elaborate on your selection, please do so here:

* 12. In general, how satisfied were you with the ***air quality/freshness*** in the building prior to DATE?

- ○ Very dissatisfied
- ○ Dissatisfied
- ○ Somewhat dissatisfied
- ○ Neither satisfied nor dissatisfied
- ○ Somewhat satisfied
- ○ Satisfied
- ○ Very satisfied
- ○ Don't know

* 13. What was the source of your dissatisfaction related to the building ***air quality/freshness*** prior to DATE? Select all that apply.

- [ ] Unpleasant/undesirable odors
- [ ] Stuffy air
- [ ] Dust
- [ ] Smoke
- [ ] Too humid
- [ ] Too dry
- [ ] Fumes
- [ ] Other (please specify)
- [ ] Don't know

14. If you'd like to elaborate on your selection, please do so here:

* 15. Did you notice any ***maintenance activities*** on the heating, ventilation, and air conditioning system while you were in the building, prior to DATE?

- ( ) Yes
- ( ) No
- ( ) Don't know

* 16. How disruptive were the ***maintenance activities*** you observed prior to DATE? Select all that apply.

- ◯ Extremely disruptive
- ◯ Very disruptive
- ◯ Somewhat disruptive
- ◯ A little disruptive
- ◯ Not at all disruptive
- ◯ Don't know

17. What was the source/cause of the disruption from ***maintenance activities*** prior to DATE? Select all that apply.

- ☐ Too noisy
- ☐ Asked to relocate
- ☐ Blocked access
- ☐ Increased foot traffic
- ☐ Other (please specify)
- ☐ Don't know

18. If you'd like to elaborate on your selection, please do so here:

* 19. In general, what was your ***thermal comfort*** while in the building after DATE?

- ◯ Hot
- ◯ Warm
- ◯ Slightly warm
- ◯ Neutral
- ◯ Slightly cool
- ◯ Cool
- ◯ Cold
- ◯ Don't know

* 20. In general, how satisfied were you with the ***temperature*** in the building after DATE?

- Very dissatisfied
- Dissatisfied
- Somewhat dissatisfied
- Neither satisfied nor dissatisfied
- Somewhat satisfied
- Satisfied
- Very satisfied
- Don't know

21. What was the source of your dissatisfaction related to the ***temperature*** after DATE? Select all that apply.

- [ ] Air movement too high
- [ ] Air movement too low
- [ ] Incoming sun
- [ ] Drafts from windows
- [ ] Drafts from vents
- [ ] Hot/cold surrounding surfaces (floor, ceiling, walls, or windows)
- [ ] Heating/cooling system does not respond quickly enough to thermostat
- [ ] Other (please specify)
- [ ] Don't know

22. If you'd like to elaborate on your selection, please do so here:

* 23. In general, how satisfied were you with the ***air movement*** in the building after DATE?

- Very dissatisfied
- Dissatisfied
- Somewhat dissatisfied
- Neither satisfied nor dissatisfied
- Somewhat satisfied
- Satisfied
- Very satisfied
- Don't know

* 24. What was the source of your dissatisfaction related to the ***air movement*** after DATE? Select all that apply.

- Stuffy (not enough air movement)
- Drafty (too much air movement)
- Too dry
- Too humid
- Other (please specify)
- Don't know

25. If you'd like to elaborate on your selection, please do so here:

* 26. In general, how satisfied were you with the level of ***noise*** from the heating, ventilation, and cooling system after DATE?

- Very dissatisfied
- Dissatisfied
- Somewhat dissatisfied
- Neither satisfied nor dissatisfied
- Somewhat satisfied
- Satisfied
- Very satisfied
- Don't know

* 27. What was the source of your dissatisfaction related to the heating, ventilation, and cooling system ***noise*** after DATE? Select all that apply.

- ☐ Loud operation
- ☐ High frequency noises
- ☐ Low frequency noises
- ☐ Motor noises
- ☐ Hissing/air movement noises
- ☐ Other (please specify)
- ☐ Don't know

28. If you'd like to elaborate on your selection, please do so here:

* 29. In general, how satisfied were you with the ***air quality/freshness*** in the building after DATE?

- ○ Very dissatisfied
- ○ Dissatisfied
- ○ Somewhat dissatisfied
- ○ Neither satisfied nor dissatisfied
- ○ Somewhat satisfied
- ○ Satisfied
- ○ Very satisfied
- ○ Don't know

* 30. What was the source of your dissatisfaction related to the building ***air quality/freshness*** after DATE? Select all that apply.

- [ ] Unpleasant/undesirable odors
- [ ] Stuffy air
- [ ] Dust
- [ ] Smoke
- [ ] Too humid
- [ ] Too dry
- [ ] Fumes
- [ ] Other (please specify)
- [ ] Don't know

31. If you'd like to elaborate on your selection, please do so here:

* 32. Did you notice any ***maintenance activities*** on the heating, ventilation, and air conditioning system while you were in the building, after DATE?

- ○ Yes
- ○ No
- ○ Don't know

* 33. How disruptive were the ***maintenance activities*** you observed after DATE? Select all that apply.

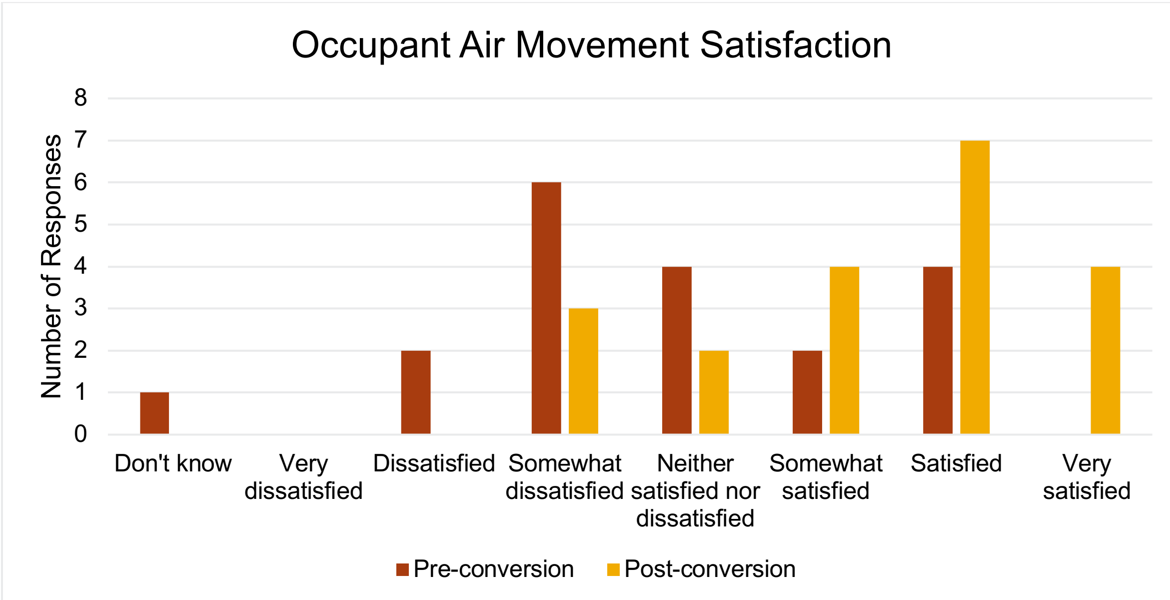
- ○ Extremely disruptive
- ○ Very disruptive
- ○ Somewhat disruptive
- ○ A little disruptive
- ○ Not at all disruptive
- ○ Don't know

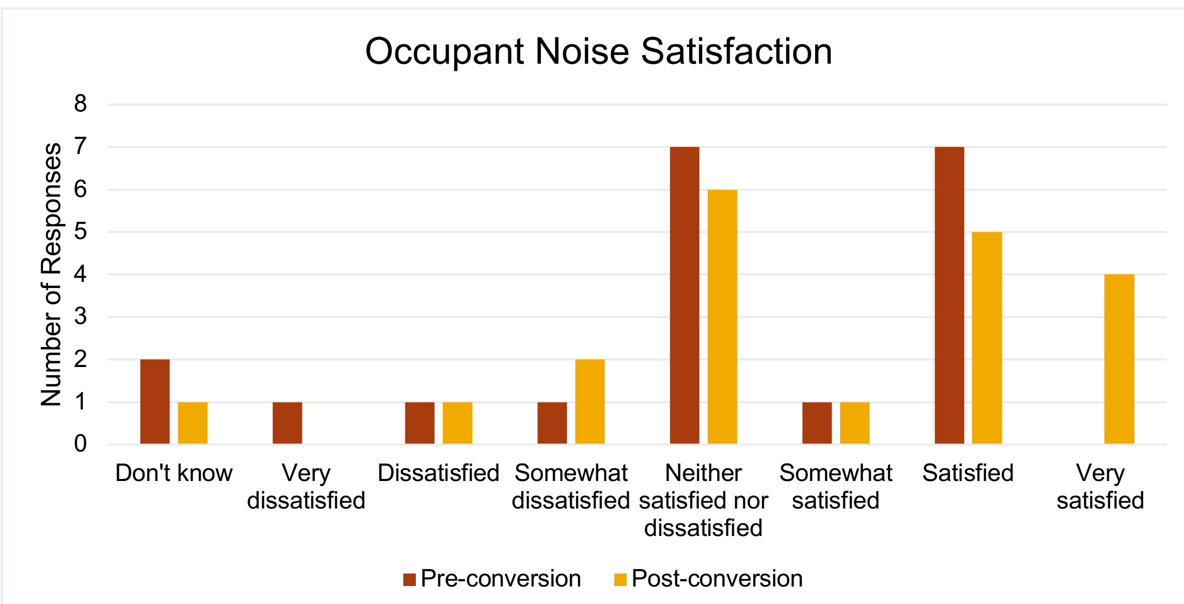
34. What was the source/cause of the disruption from ***maintenance activities*** after DATE? Select all that apply.

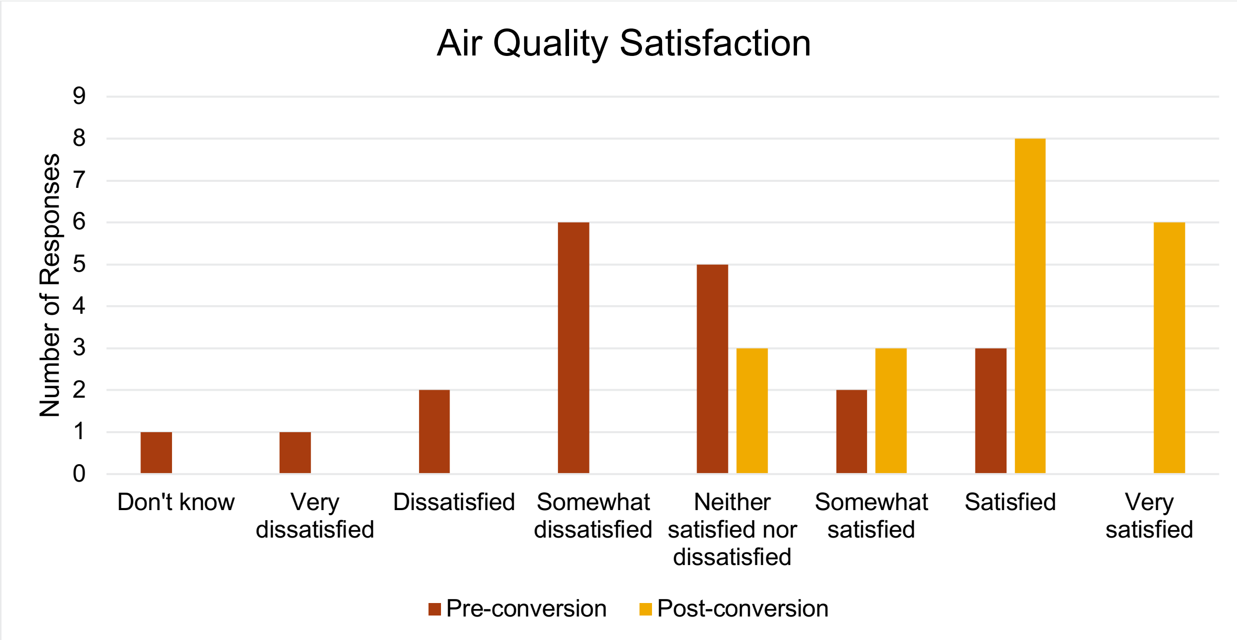
- [ ] Too noisy
- [ ] Asked to relocate
- [ ] Blocked access
- [ ] Increased foot traffic
- [ ] Other (please specify)
- [ ] Don't know

35. If you'd like to elaborate on your selection, please do so here:

Appendix D – IEQ Occupant Survey Results






Air Quality Satisfaction
Number of Responses
0
1
2
3
4
5
6
7
8
9
Don't know
Very dissatisfied
Dissatisfied
Somewhat dissatisfied
Neither satisfied nor dissatisfied
Somewhat satisfied
Satisfied
Very satisfied
Pre-conversion
Post-conversion

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