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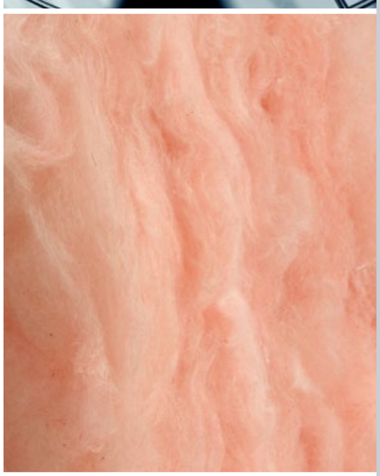
RENEWABLE ENERGY

Field Validation of a Smart Energy Recovery Ventilation System Using Low-Cost Indoor Air Quality Sensors

March 2021



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Field Validation of a Smart Energy Recovery Ventilation System Using Low-Cost Indoor Air Quality Sensors

Prepared for:
U.S. Department of Energy Building America Program
Office of Energy Efficiency and Renewable Energy

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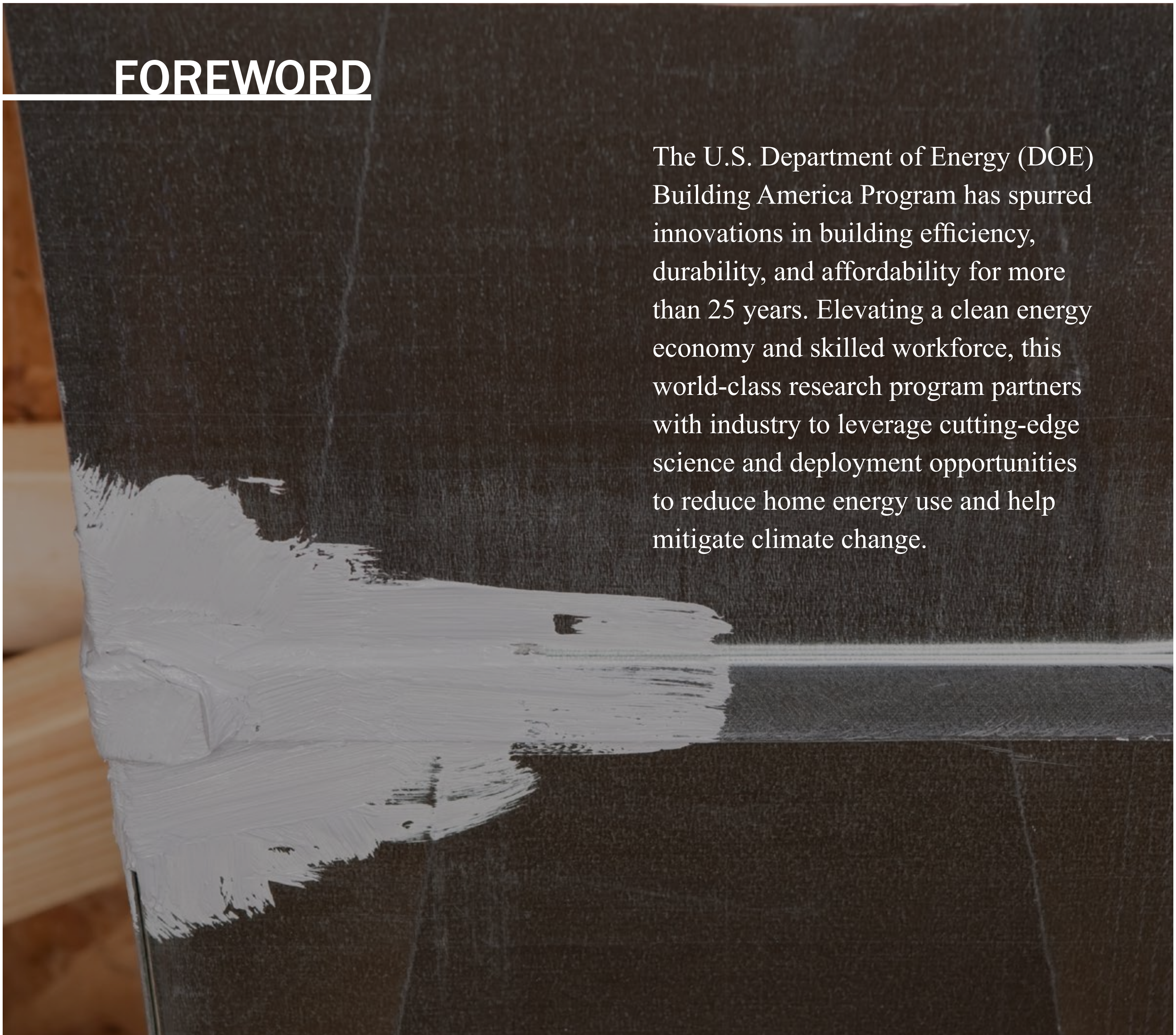
This material is based upon work supported by the Department of Energy's Office of Energy Efficiency and Renewable Energy (EERE) under the Building Technologies Office under Award Number EE0007575.

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

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

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



FOREWORD

The U.S. Department of Energy (DOE) Building America Program has spurred innovations in building efficiency, durability, and affordability for more than 25 years. Elevating a clean energy economy and skilled workforce, this world-class research program partners with industry to leverage cutting-edge science and deployment opportunities to reduce home energy use and help mitigate climate change.

In cooperation with the Building America Program, the Southface team is one of many Building America teams working to drive innovations that address the challenges identified in the program's Research-to-Market Plan.

This report, *Field Validation of a Smart Energy Recovery Ventilation System Using Low-Cost Indoor Air Quality Sensors*, is a field study of a smart ventilation system that can help low-load homes in humid environments maintain acceptable indoor humidity conditions while providing adequate ventilation according to ASHRAE 62.2.

As the technical monitor of the Building America research, the National Renewable Energy Laboratory encourages feedback and dialogue on the research findings in this report as well as others. Send any comments and questions to building.america@ee.doe.gov.

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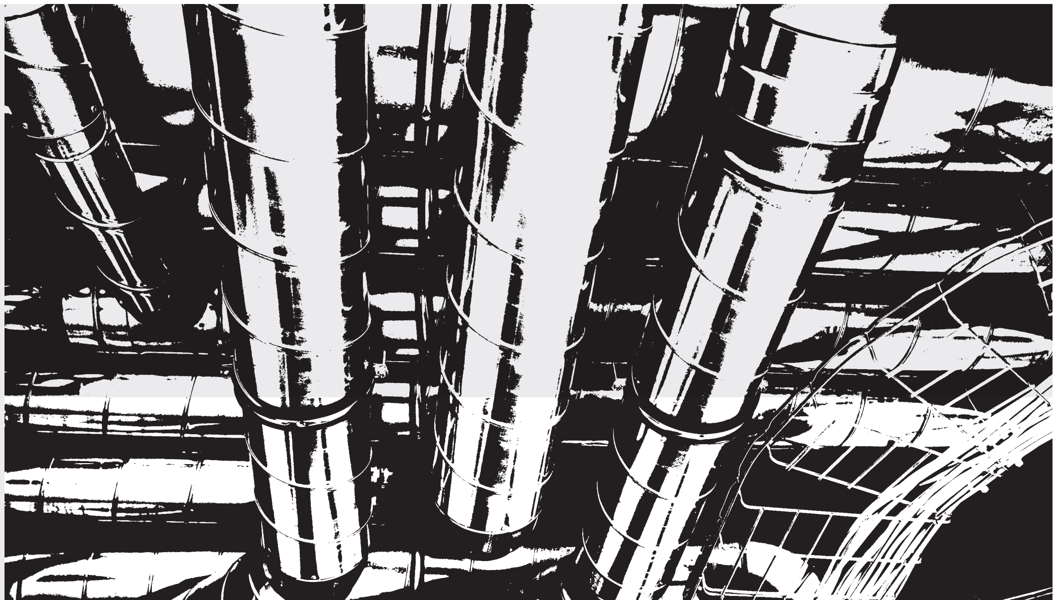


LIST OF ACRONYMS

A/C	air conditioning
ACH	air changes per hour (ACH_{50} indicates air changes per hour at 50 pascals)
AHRI	Air-Conditioning, Heating, and Refrigeration Institute
AHU	air handling unit
CFIS	central fan integrated supply
CFM	cubic feet per minute (CFM_{25} and CFM_{50} indicate cubic feet per minute at 25 and 50 pascals, respectively)
CO_2	carbon dioxide
CT	current transducer
CV	coefficient of variation
DOE	U.S. Department of Energy
EATR	exhaust air transfer ratio
EER	energy efficiency ratio
ERV	energy recovery ventilator
HVAC	heating, ventilating, and air conditioning
IAQ	indoor air quality
kWh	kilowatt-hour
LBNL	Lawrence Berkeley National Laboratory
MERV	minimum efficiency reporting value (filter efficiency)
NREL	National Renewable Energy Laboratory
OA	outside air
PM	particulate matter
QAQC	quality assurance/quality check
RH	relative humidity
RMSD	root-mean-square deviation
RPD	relative percent difference
SEER	seasonal energy efficiency ratio
TMY	typical meteorological year
T/RH	temperature and relative humidity
W	watts
w.c.	water column

EXECUTIVE SUMMARY

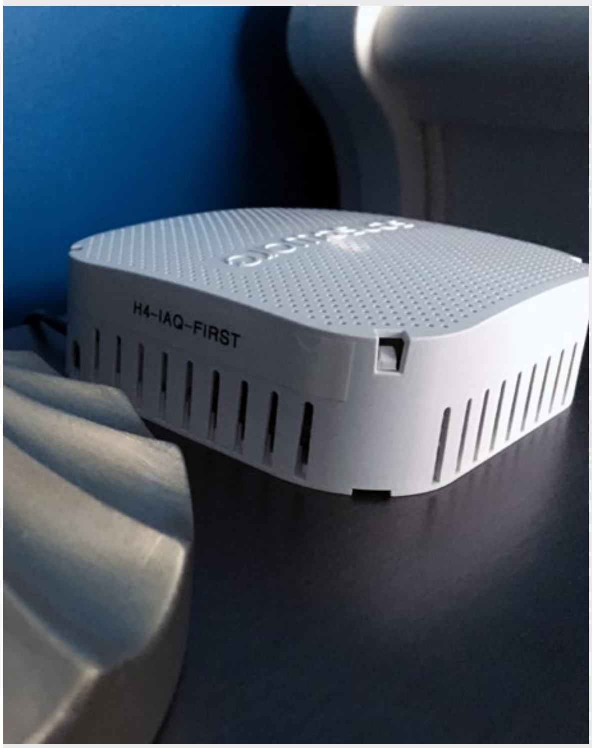
This project is a field validation, using low-cost indoor air quality (IAQ) sensors, of a smart ventilation system that can help low-load homes in humid environments maintain acceptable indoor humidity conditions while providing adequate ventilation according to ASHRAE 62.2.

The objectives of this research were to (1) address builders' concerns with mechanical ventilation in humid environments and (2) answer the question of whether smart control logic helps with occupant comfort and the creation of a more acceptable indoor environment.

To address the objectives of the study, the Southface team collected field data for one year in four Charleston, South Carolina, new construction homes in order to determine the differences in occupant comfort; comfort metrics; IAQ; and heating, ventilating, and air-conditioning (HVAC) energy consumption when toggling biweekly between an energy recovery ventilator (ERV) operating continuously and an ERV operating with smart, time-varying humidity control logic.

The smart ventilation algorithm under consideration in this field test did create a less humid indoor environment on an annual basis as quantitatively measured through temperature and relative humidity (T/RH) readings, expressed most discernably as "percentage of time above 60% RH" and "percentage of time above 55°F dewpoint." However, the difference it made was inconsistent during the spring, summer, and fall months, and it was only directionally consistent during the winter months. We suspect that this is primarily due to the long runtimes and concomitant dehumidification activity of the air-conditioning (A/C) units in response to the high sensible loads in Charleston. The effect of the smart ventilation algorithm was not discernable to the occupants in this study, as recorded through seasonal surveys.

There was a measurable, albeit small, difference in both CO_2 and particulate matter (PM) concentrations when comparing smart and continuous ERV modes. We could directly compare PM levels between modes using mixed effect regression modeling, which showed to a statistically significant degree that PM_1 and $PM_{2.5}$ concentrations were lower in the smart mode. Although the CO_2 levels were not able be compared using the same approach, every microenvironment within every house was measured to have slightly higher median levels of CO_2 in smart mode compared to continuous mode. The mean CO_2 levels were also higher in smart mode to a statistically significant degree, per t-test results, for every house and microenvironment except for the House 1 master bedroom.



The average radon levels were extremely low in all houses due to the type of foundation construction used, so differences were negligible between ERV modes. It should be emphasized that although we did measure differences by mode for the pollutants, which for some were statistically significant, differences in the physical concentrations were small. Based on these findings, we believe that caution should be taken when making inferences regarding the role of ERV mode in either reducing or enhancing indoor pollutant levels.

We were able to compare the test homes with BEopt™-modeled energy consumption for the A/C condensing unit end use and the ERV itself, but not for the air handling unit (AHU) or gas heating end uses. The A/C savings prediction was not very accurate in terms of raw kWh savings, but was reasonably accurate in terms of A/C savings percentage (5.2% savings predicted vs. 7.6% actual, on average). The ERV savings prediction was accurate both with regard to kWh and kWh percentage savings.

The BEopt house models, which compared various ventilation options, showed 2.6%–3.3% overall electricity savings and very marginal gas savings for smart mode compared to continuous mode. The central fan integrated supply (CFIS) at Q_{tot} models used 3.0%–7.1% more electricity and 4.9%–12.0% more gas than the baseline continuous ERV model. The CFIS at Q_{fan} models used 0.2%–3.8% more electricity and 0.2%–3.8% less gas than the baseline continuous ERV model. The overall lowest electricity and gas use was for a continuous ERV sized at the exact Qfan requirement per ASHRAE 62.2-2016 (3.4%–4.7% kWh savings and 0.9%–2.3% gas savings over smart mode).

The actual relative exposure as defined in ASHRAE 62.2-2016 Appendix C for each house was similar to the prediction based off BEopt simulation data. ERV field performance was also calculated, showing in-situ performance consistent with lab tests in the literature.



Table of Contents

List of Figures

List of Tables

1 Introduction

1.1 Problem Statement

Building airtightness is crucial to lowering the energy use of homes, but mechanical ventilation is necessary to provide optimal indoor air quality (IAQ). However, resistance to mechanical ventilation is one of the reasons for builder push-back on increasing building enclosure airtightness requirements for state energy codes, as seen in Florida, Georgia, Louisiana, and others. Builders are resistant to cost increases, but perhaps more importantly, they fear the introduction of humidity from outside, especially in a hot-humid climate.

Smart ventilation solutions that minimize indoor humidity at an acceptable cost to production builders have the potential to overcome this barrier while providing the important IAQ benefits necessary for occupant health.

1.2 Scope and Objectives of the Study

This project is a field validation, using low-cost IAQ sensors, of a smart ventilation system that is designed to help low-load homes in humid environments maintain acceptable indoor humidity conditions while providing adequate ventilation according to ASHRAE 62.2-2016.

The Southface team collected field data for one year in four Charleston, South Carolina, new construction homes in order to determine the differences in occupant comfort; comfort metrics; IAQ; and heating, ventilating, and air-conditioning (HVAC) energy consumption when toggling biweekly between an energy recovery ventilator (ERV) operating continuously and an ERV operating with smart, time-varying humidity control logic.

The team continuously measured temperature (T); relative humidity (RH); carbon dioxide (CO_2); particulate matter at 1 micron (PM_1), 2.5 microns ($PM_{2.5}$), and 10 microns (PM_{10}); and radon. Each of these metrics, except radon, were measured in multiple locations within each home, as well as outdoors. The HVAC system energy usage and ERV performance was also continuously monitored throughout the year, and occupant feedback regarding their comfort was obtained using brief surveys.

The objectives of this research were to address builders' concerns with mechanical ventilation in humid environments and answer the question of whether the smart control logic helps with occupant comfort and the creation of a more acceptable indoor environment.

1.3 Research Questions

This study addressed the following research questions:

1. Does a recently developed smart ventilation algorithm that considers outdoor temperature and RH in a market-ready ERV create a more acceptable indoor environment, expressed qualitatively as occupant comfort and quantitatively through indoor T/RH measurements, compared to continuous operation of that ERV in humid climates?

2. Using low-cost IAQ sensors whose performance has been independently verified, is there a discernable difference between measured indoor air pollutants when comparing continuous and smart ERV operation modes?
3. How much space-conditioning energy is saved and how accurately can BEopt™ models (with customized time-varying ventilation scripts) predict HVAC energy savings for test homes switching between smart and continuous operation modes?

1.4 Background and Literature Review

IAQ has become an ever-increasing priority for building performance, as seen in research conducted by Lawrence Berkeley National Laboratory (LBNL)[1] and others. Given the amount of time most Americans spend indoors at home (Klepeis et al. 2001), residential exposure in particular comprises a substantial fraction of total daily exposure for many pollutants. It has been estimated that the cumulative health impacts from inhalation of indoor air pollutants in U.S. residences are between 400 and 1,100 DALYs (Disability Adjusted Life Years) annually per 100,000 people (Logue et al. 2011). This puts it in the range of road traffic accidents and heart disease (Guyot et al. 2017). Indoor sources, as well as infiltration of ambient pollution indoors, remain a driver of adverse cardiorespiratory morbidity response, as well as specific cancers (WHO 2010).

Today, new construction approaches and building operational technologies have emerged that add greater opportunities for control of indoor building environments, including IAQ. We have also entered into an era of distributed and optimized sensing technologies. Despite the considerable evidence linking specific building construction and building performance parameters to measures of IAQ, there is little to date on how these new sensors truly influence IAQ and building operational costs. The prices of these new sensors and monitors are decreasing to a point where it may become just as common for a building scientist to have a PM monitor as it is for them to have a manometer. Further, sensors for IAQ (beyond CO_2) as well as wi-fi/internet communication will likely be embedded in future smart HVAC equipment (Guyot et al. 2017).

Reference method monitors used to measure various components of IAQ are often expensive ($5,000–$10,000), with additional associated calibration and maintenance costs. There is a need for affordable and accurate long-term measurement of metrics in high-performance homes, including looking for interactions between IAQ metrics and building performance characteristics such as building airtightness (air changes per hour, or ACH), ventilation rate, cooking fuel type, and others. The "low-cost" IAQ sensors used in this study are ones that are commercially available and are in the sub-$100 range, situated for potential future integration into smart ventilation solutions.

[1] LBNL IAQ work can be found at https://iaqscience.lbl.gov/.

Barring estimates of both health and operational costs/benefits, marketplace proliferation of advanced IAQ solutions will be uncertain. Performance-based and field-validated ventilation systems are necessary for the evolution of the ASHRAE 62.2 standard, continued development of smart ventilation systems, and acceleration of manufacturers' ability to target solutions for optimal performance.

Basic mechanical ventilation has become standard in new high-performance homes, some building codes, and home performance and weatherization programs, but current solutions are limited (e.g., climate, control capability, pollutant source, cost limitations), and standards do not help optimize either IAQ or energy performance related to the ventilation system or heating and cooling (Straube and Grin 2010; DOE 2015).

For a significant portion of the country, standard residential new construction has yet to embrace intentional fresh air ventilation. In fact, resistance to prescribed mechanical ventilation is one of the reasons for builder push-back on increasing building enclosure airtightness code requirements, as seen in Florida, Georgia, and Louisiana in recent years. Builders are resistant to cost increases, but perhaps more importantly, they fear the introduction of humidity from outside. One potential avenue toward mitigating concerns is to focus on improved ventilation solutions. Ventilation solutions that minimize indoor humidity at an acceptable cost to production builders have the potential to overcome this barrier while providing the important IAQ benefits necessary for occupant health.

Field experiments and simulations exploring different smart ventilation controls—including outdoor temperature-based controls, occupancy-based controls, and current/24-hour historical outdoor T/RH controls—have been performed in another Building America project (Martin et al. 2018). That project's findings in a hot-humid climate showed that these various control options can be used to meet ASHRAE 62.2-2016 relative exposure requirements while providing potential energy savings (5.5%–10% cooling savings) and comfort improvements. This study aims to expand on these findings by testing a market-ready smart ERV in occupied homes for 12 months, while monitoring IAQ and energy usage.

Smart ventilation technologies also pose a challenge in common residential energy modeling and simulation software, such as BEopt and REM/Rate. This software was previously incapable of manipulating whole-house ventilation fan runtime without a customized script, regardless of fan flow or ventilation technique. Southface worked with the National Renewable Energy Laboratory (NREL) to investigate and implement methods to accurately "control" emerging ventilation strategies in the software programs, including both T/RH-based ERV and central fan integrated supply (CFIS) ventilation techniques.

The hypothesis for this study is that the smart ventilation algorithm in a market-ready ERV can help homes in humid environments maintain more acceptable indoor humidity conditions while providing adequate ventilation according to ASHRAE 62.2-2016. To test this hypothesis, the Southface team collected field data to determine the differences in occupant comfort, comfort metrics, IAQ, and HVAC energy consumption between an ERV operating continuously and an

ERV with smart, time-varying humidity control logic. The objectives were to address some of the builders' concerns and answer the question of whether the smart control logic helps with occupant comfort and the creation of a more acceptable indoor environment. Specifically, this project aimed to answer the following research questions:

1. Does a specific smart ventilation algorithm that considers outdoor temperature and relative humidity in a market-ready ERV create a more acceptable indoor environment, expressed qualitatively as occupant comfort and quantitatively through indoor T/RH measurements, compared to continuous operation of that ERV in humid climates?
2. Using low-cost IAQ sensors whose performance has been independently verified, is there a discernable difference between measured indoor air pollutants when comparing continuous and smart ERV operation modes?
3. How much space-conditioning energy is saved and how accurately can BEopt models (with customized time-varying ventilation scripts) predict HVAC energy savings for test homes switching between smart and continuous operation modes?

2 Methodology

2.1 Research Design

2.1.1 Research Design Overview

The Southface team designed this field validation study to qualitatively investigate occupant comfort while quantitatively measuring comfort metrics and HVAC energy consumption in four ERV-outfitted, new-construction homes in Charleston, South Carolina. The ERVs were toggled between continuous and smart operation modes on a biweekly basis. In addition, low-cost IAQ sensors were deployed inside and outside each home to monitor air quality metrics. The pollutant concentration data were analyzed to determine if a discernable difference existed between measured indoor air pollutants when comparing continuous and smart ERV operation modes.

Southface collaborated with builder partner Beazer Homes to incorporate smart ERV systems with humidity-control logic in the design and construction of the new homes. Building performance characteristics of the new homes, such as ventilation air flow, airtightness, and duct system air leakage were measured before the field test. Ventilation airflow was remeasured at the end of the field test. Details of building performance characteristics are provided in Section 3.1. Southface deployed the low-cost sensor packages to monitor and record both indoor and outdoor air quality metrics of these buildings, as well as sensors for ventilation system and heating and cooling energy consumption. Details of the data collection equipment are provided in Section 2.3.1. Additionally, Southface obtained occupant feedback regarding their comfort using a brief three-question survey two times per season.

The impact of smart ERV versus continuous ERV systems on occupant comfort, T, RH, CO_2, PM, and building energy consumption was evaluated throughout the year. Southface also developed BEopt models (with customized time-varying ventilation scripts) and examined how accurately they predicted HVAC energy usage and savings for each of the test homes.

2.1.2 Test Home Characteristics

All four test homes were located within a 700-ft radius in the same neighborhood in Charleston, South Carolina. The homes were ENERGY STAR® v3 certified and were generally built to the following standard Beazer Homes specifications:

Table 1. Beazer Homes Standard Construction Specifications

Group Name	Category	Beazer Homes Specifications/ BEopt Inputs
Ceilings/Roofs	Unfinished Attic	R-49 fiberglass blown-in; vented
Walls	Exterior	R-15 2x4
Windows	Window Type	U-0.36, SHGC 0.28
Airflow	Infiltration	4 ACH_{50}
	Ventilation	CFIS (typical) Broan ERVS100S (for this study) Compliant with ASHRAE 62.2-2010, including bath and kitchen ventilation (typical) Compliant with ASHRAE 62.2-2016, including bath and kitchen ventilation (for this study)
	Duct Leakage	4 CFM_{25} per 100 ft^2 leakage to outside 8 CFM_{25} per 100 ft^2 total leakage
Major Appliances	Refrigerator	Standard
	Cooking Range	Standard, gas
	Dishwasher	ENERGY STAR
Lighting	Lighting	100% Compact fluorescent lamp (CFL) bulbs
Space Conditioning	Cooling Component	SEER 14 Single Stage
Space Conditioning	Heating Component	Variable speed, 96% annual fuel utilization efficiency, natural gas furnace
Water Heating	Water Heater	Gas, tankless, 0.82 EF

Every home in the neighborhood was a two-story elevated plan, built on approximately 9 ft concrete piers, as they are located in a flood zone. Each test home was chosen because of similar layout and square footage (2,300 ± 100 ft^2). An example of a typical house in the neighborhood can be seen in Figure 1. The tested and verified actual values used in modeling each house can be seen in Section 3: Results.

Figure 1. Photo of typical test house having a blower door test performed on it

2.1.3 Low-Cost IAQ Sensor Selection

Southface conducted several technical meetings with stakeholders and partners to identify the most important and measurable IAQ pollutants from a list of more than 20 impactful air quality pollutants. The team identified six air quality metrics that were indicative of overall IAQ that may be measured with commercially available low-cost sensors and another seven considered to be impactful but without corresponding low-cost sensors.

Southface sourced sensors for five of these air quality metrics and tested them in the Southface Eco Office and in UL Environment's test chambers prior to deployment. The low-cost sensor not sourced was for total volatile organic compounds and was excluded due to the known unreliability of the sensor technology at the time of acquisition. These metrics and corresponding sensors can be seen in Table 2. The low-cost IAQ sensors used in this study are ones that were commercially available and in the sub-$100 range (for each individual sensor), situated for potential future integration into smart ventilation solutions. All sensors except for radon were packaged by Senseware in wireless sensor packages that were placed throughout each test home. Additional information on the sensors can be found in Section 2.2: Data Collection Instruments and Procedures.

Table 2. IAQ Metrics and Sensors Used in This Study

IAQ Metric	Sensor
PM	Plantower PMS5003
CO_2	Telaire T6713-5K
T	Sensirion SHT21
RH	Sensirion SHT21
Radon	Airthings Wave

2.1.4 Smart ERV Specifications

The Broan smart ERV used in this study (model number ERVS100S), sized to service 90% of new construction, features in-line temperature and humidity sensors and a control algorithm that limits runtime when outdoor conditions are extremely humid.

The Broan ERVS100S is a balanced ventilation solution specifically designed for houses in southern regions, where the temperature is above -10°C (14°F) throughout the year. The sensible recovery efficiency is 57% and the total recovery efficiency is 38% on high speed. Built-in sensors located in the outdoor air intake side of the ERV monitor outdoor dry-bulb temperature and RH every 10 minutes.[2]

Once the sensors detect humidity levels above the threshold limits, continuous ventilation is terminated. The ERV remains off for 50 minutes, and then resumes operation at the specified flow rate for 10 minutes. After 10 minutes of operation, it will take another reading of temperature and RH and repeat the cycle. Therefore, the building will receive fresh air for a minimum of 4 hours/day even if extended high RH levels are detected for 24 hours consecutively. Alternatively, if the humidity thresholds are not exceeded, it will run continuously even if the ASHRAE 62.2 requirement is exceeded.

The unit will switch to standby mode upon reading a dewpoint over the limits indicated in Table 3. “Position” in Table 3 refers to a contractor/user setting on the ERV.

Table 3. Maximum Allowed Outside Dewpoint Temperature (°F)

Position	Outside Temp <73°F	Outside Temp ≥73°F
OFF	-	-
+	62.6	77.0
N	59.0	73.4
-	55.4	69.8

For this study, the ERVS100S was set to the factory threshold, *N*, to operate in time-varying mode, and the ventilation mode was set to high speed, or 105 cfm nominal (Figure 2). To operate in “continuous mode,” the threshold will be set to OFF. Southface worked with Broan (the smart ERV manufacturer) and Senseware in order to automatically toggle the ERVS100S between N and OFF modes on a biweekly basis.

According to Figure 2, the RH limits of the distributed air are calculated considering the energy recovery of the unit with the assumption that the indoor conditions are 24°C (75°F) and 50% RH.

[2] From the Broan ERVS100S Installation Guide: 57% sensible recovery efficiency is for 106 CFM, assuming heating season with a supply temperature of 32°F. 38% total recovery efficiency is 38% for 106 CFM, assuming cooling season with a supply temperature of 95°F. These values were not provided for the alternate season.

Control

Ventilation modes

Position	Mode	Description
SB*	Standby	Unit is off. Unit can be activated in high speed by the VB20W 20-minute push-button control, if applicable
INT	Intermittent	Unit works 20 minutes per hour in low speed. Unit can be activated in high speed by the VB20W 20-minute push-button control, if applicable.
1	Low Speed	Unit runs at 65 cfm. Unit can be activated in high speed by VB20W 20-minute push-button, if applicable.
2	High Speed	Unit runs at 105 cfm. Unit can be activated in high speed by the VB20W 20-minute push-button control, if applicable.

*Factory setting

Position	Description	Distributed air RH* Outside temp <73°F	Distributed air RH* Outside temp ≥73°F
OFF	Relative humidity limit is deactivated	-	-
+	Higher relative humidity limit	Up to 60%	Up to 80%**
N	Factory set relative humidity limit	Up to 55%	Up tp 75%**
-	Lower relative humidity limit	Up to 50%	Up to 70%**

* The RH limit of distributed air is calculated at 75°F.

** When the outside temperature is equal or above 73°F, the maximum relative humidity level accepted is higher considering that the air conditionning will partly dehumidify the incoming fresh air after it is distributed and mixed with the conditionned inside air.

Figure 2. Broan ERVS100S control positions

Figure from Broan Installation Guide (Broan N.D.)

The ERV can be installed fully ducted or connected to the ducted HVAC system on the return side, as specified in the installation instructions. A schematic of the preferred design is illustrated in Figure 3. In practice, due to construction constraints, House 1 was installed as specified in Figure 3 and houses 2–4 were installed with the fresh air supply duct terminating in the upstairs hallway, adjacent to one of the air handling unit (AHU) return grilles. It is worth noting that House 1's air-conditioning (A/C) performance may be slightly different as a result of fresh air supply being ducted to return. The ERV was located in the attic of all test homes. Round, 6-inch, R8 insulated flexible fresh air ducts were used for all ERV ducting. The stale air from the home was exhausted from a dedicated grill located in either the attic wall or the soffit, as shown in the figure below.

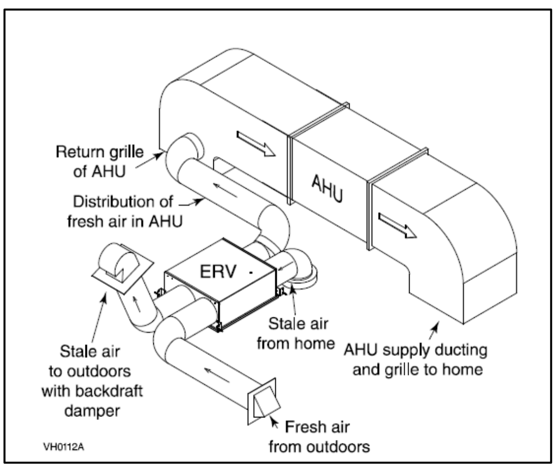


Figure 3. Planned design for installation of ERV

Figure from Broan Installation Guide (Broan N.D.)

2.1.5 Smart ERV Sizing

Because the exact floorplans and house specifications were unknown when initially sizing the ERV, expected average values of 2,300 ft^2 floor area, 4 bedrooms, and infiltration of 4 ACH_{50} were used to determine the continuous mechanical ventilation requirements per ASHRAE 62.2-2016. The resulting continuous total ventilation rate (Q_{tot}) and continuous fan flow rate (Q_{fan}) were 106.5 cfm and 60.6 cfm, respectively (ASHRAE 2016).

However, because the smart ERV does not run continuously, sizing of the unit cannot simply be done using this typical ASHRAE 62.2 calculation, which considers only the square footage and number of bedrooms. *Relative exposure* to a hypothetical continuously emitted pollutant was calculated for the time-varying ERV using ASHRAE 62.2-2016 Section 4.5 and Appendix C, as well as the ASHRAE 62.2-2016 User Guide. The principal behind Section 4.5 is to verify that an occupant using a proposed variable ventilation system will have no more annual exposure to a constant-source contaminant than they would if a constant total flow were provided. In order to comply with this standard for weather-dependent time-varying ventilation, relative exposure must be limited to 5.0 for all time steps. The annual average relative exposure also must be no greater than 1.0 to comply.

To model the smart ERV behavior, Southface collaborated with NREL to develop an energy management system program within BEopt to accurately control the on/off schedule for the Broan ERVS100S. The energy management system uses the Broan ERVS100S control logic in conjunction with typical meteorological year (TMY) weather data to control the on/off time for the ERV in 10-minute intervals. The unit switches to standby upon reading a dewpoint over the limits from Table 3. This control is activated in BEopt using a customized "trigger" in the Option Manager.

The 10-minute ERV behavior, paired with TMY weather data, was then exported from BEopt. In order to calculate relative exposure, the actual fan ventilation rate at each time step ($Q_{fan,i}$) was set to the ERVS100S high-speed fan setting of 105 cfm. Additional variable values were based on house geometry, location, and current Beazer Homes construction practices, such as airtightness of 4.0 ACH_{50}. Both the "annual average method" and the "smaller time step method" (Δt = 10 minutes) were used to compute relative exposure. The annual average method resulted in lower exposure values, and both cases are presented in Figure 4. The figure demonstrates that peak relative exposure for both methods never reaches the threshold of 5.0. The peak relative exposure using the annual average method is 1.71, and the average relative exposure is 0.93. The peak relative exposure using the smaller time step method is 3.21, and the average relative exposure is 1.09.

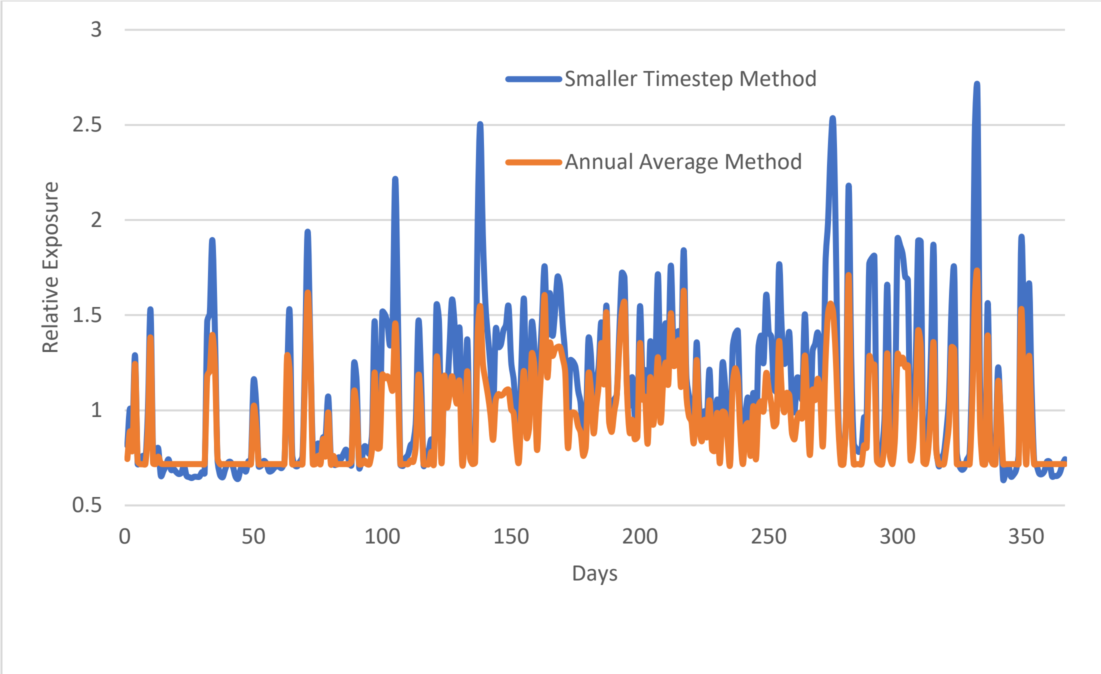


Figure 4. Calculated relative exposure for ERVS100S in Charleston, South Carolina (start date Jan 1)

Additionally, annual average relative exposure was calculated for a range of fan flows using both methods (Figure 5).

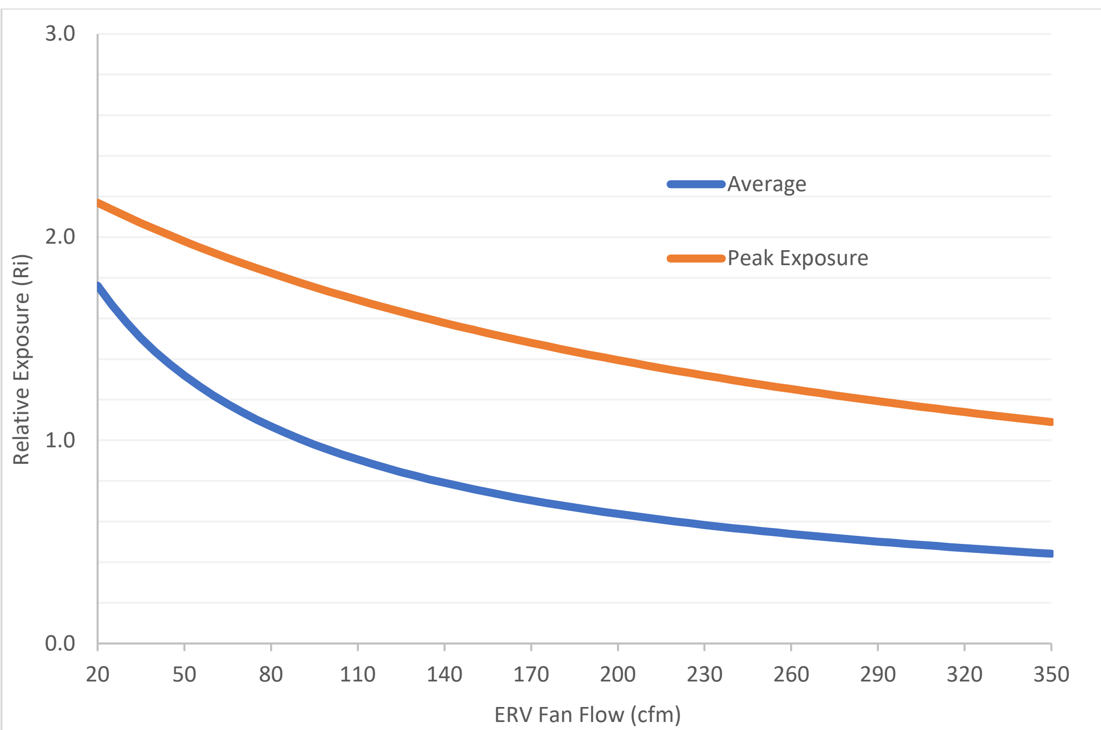


Figure 5. Annual average relative exposure for ERV varying fan flows (annual average method), Charleston, South Carolina

The end result of the above relative exposure analysis was the choice to set the ERV speed to high speed (105 cfm nominal), rather than low speed (65 cfm nominal) during smart mode periods. Using the default factory humidity threshold, *N*, and the high-speed mode fan flow rate of 105 cfm, the Broan ERVS100S complies with ASHRAE 62.2-2016. For reference, this analysis shows that the minimum intermittent airflow rate required to achieve an annual average relative exposure of 1.0 for these test homes is 90 cfm using the annual average method.

The speed chosen for continuous mode periods was also high speed (105 cfm nominal) because the estimated Q_{fan} requirement of 60.2 cfm would not be satisfied by low speed (65 cfm nominal) when the exhaust air transfer ratio (EATR) and the as-installed duct losses were taken into account. The as-installed supply airflows ranged from 80.5%–95.1% of nominal and the EATR was 5.0%, so the delivered cfm on low speed would be 49.7–58.7 cfm and would fail to meet ASHRAE 62.2-2016.

2.1.6 Energy Modeling of Test Homes

Energy models were constructed for each house using the NREL-developed building energy simulation tool BEopt[3] in order to compare the energy usage between various ventilation options. The energy usage of the two field-tested options (1 and 2, below) were then compared to the modeled energy usage. The five options modeled were:

1. A Broan ERVS100S in time-varying (smart) mode at the field-measured supply flow rate for each house (93.7 cfm average, but varies by house; see Table 7)
2. A Broan ERVS100S in continuous mode at the field-measured supply flow rate for each house (93.7 cfm average, but varies by house; see Table 7)
3. A Broan ERVS100S equivalent in continuous mode, exactly sized at the ASHRAE 62.2-2016 Q_{fan} requirement for each house (54.0 cfm average, but varies by house; see Table 7)
4. A CFIS system (the builder's standard ventilation method) at the ASHRAE 62.2-2016 Q_{tot} requirement for each house (106.6 cfm average, but varies by house; see Table 7)
5. A CFIS system at the ASHRAE 62.2-2016 Q_{fan} requirement for each house (54.0 cfm average, but varies by house; see Table 7).

The ERV recovery efficiencies for options 1–3, above, were referenced from the Broan ERVS100S Spec Sheet (Broan Spec Sheet N.D.). The power draw used in the models was the actual field-measured values for options 1 and 2, but the spec sheet value for option 3. The sensible and total recovery efficiency of the ERVs was assumed to be the spec sheet reported values at 105 cfm for options 1 and 2 and 64 cfm for option 3.

[3] For more information on BEopt, see: https://beopt.nrel.gov/home.

All building takeoffs were modeled in reference to the house-specific building plans and supplemented with field-tested and field-observed performance data for each house. A screenshot of one of the models can be seen in Figure 6. Default schedules and TMY data were used in the BEopt simulations, following NREL's *Building America House Simulation Protocols* (Hendron and Engebrecht 2010). The only custom schedules used were the programmed thermostat set points unique to each house. Additional modeling assumptions can be seen in Appendix D.

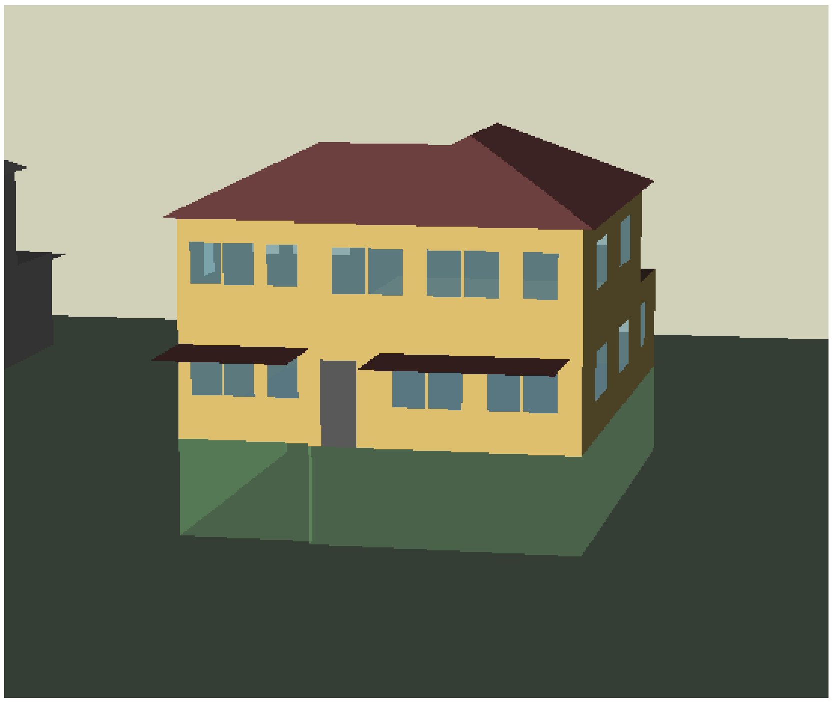


Figure 6. BEopt model screenshot

Figure 7, created by NREL, demonstrates the control logic of the ERVS100S in conjunction with TMY weather data during January in Charleston. The ERV trend illustrates that the ERV stops ventilation when the weather is outside of the outdoor dry-bulb and dewpoint temperature limits. However, even when the dewpoint limit is exceeded for several hours in a row, the unit continues to ventilate 10 minutes of every hour in order to take additional readings to determine the operation state for the next time step.

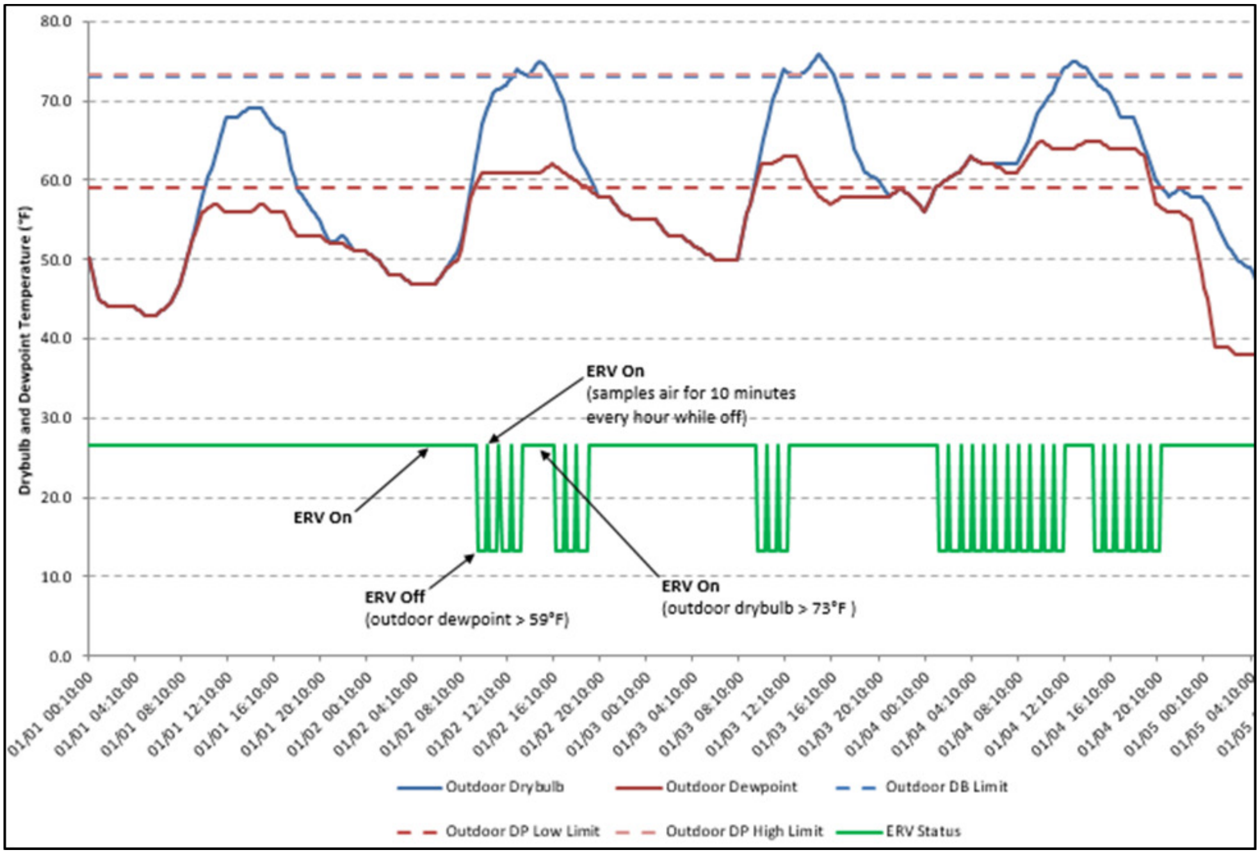


Figure 7. ERVS100S BEopt control logic

Similarly, Southface collaborated with NREL to improve the functionality of modeling CFIS ventilation systems in BEopt. NREL developed a customized script to mimic industry standard CFIS ventilation controllers that work in conjunction with the split-system heating/cooling air handler fan. A minimum number of minutes per hour of ventilation can be manipulated in the script to ensure that ASHRAE 62.2 is met for periods when the heating or cooling load is low. During these times, the CFIS fan power is non-zero because the AHU fan turns on specifically to provide ventilation. As another example, during the summer months, there are several hours where the ventilation requirement is met entirely by the call for cooling, so the additional CFIS fan power is zero during this time, and the damper on the fresh air intake duct closes toward the end of the hour. This CFIS modeling functionality was released to the general public with the publishing of BEopt v2.8.

2.1.7 Short-Term Testing

Southface performed short-term testing of the new construction test homes once occupied by homeowners in order to establish the following performance characteristics before the long-term monitoring study:

- Integrity of the building envelope (visual inspection)
- Whole-house air leakage rate

- HVAC duct tightness
- HVAC system performance (static pressures and as-installed configuration)
- ERV system flow rates
- Flow rates of exhaust fans and devices.

Additional short-term data collection included building specifications/takeoffs, plans, construction costs, and other building-specific data. Southface retested the ventilation system flow rates and the flow rates of exhaust fans and devices following the long-term monitoring study.

The whole-house air leakage rate was measured through a multipoint blower door test using TECTITE software to automatically control the blower door. Duct leakage to outside and total duct leakage was measured using duct pressurization. Local exhaust fan flows for bathroom exhaust fans and kitchen range hoods were measured at an accessible location using an exhaust fan flow meter.

Ventilation airflow at all four airstreams for the ERV, diagrammed in Figure 12, was determined by measuring in-line with a calibrated Venmar[4] pitot-tube array flow meter in two of the duct airflow streams (Figure 8, detail of flow meter accuracy in Section 2.2.1). The airflow at X_2 and X_3 were used in conjunction with the lab-tested exhaust air transfer ratio (EATR)[5] to calculate the airflow at X_1 and X_4. Venmar previously measured the EATR for each ERV by testing leakage from the exhaust stream to the supply air stream within the unit using a tracer gas test performed as per Canadian Standards Association (CSA) C439 clause 8.2.3.1. The Venmar flow meter is illustrated in Figure 8, with the installation diagram shown in Figure 9. The red arrows indicate the straight and rigid duct run required to test airflow in laminar flow conditions (3x duct diameter), and the blue arrows indicate the length of the actual flow meter (6 inches). As a secondary method, ventilation airflow was also confirmed using an Alnor LoFlo Balometer.

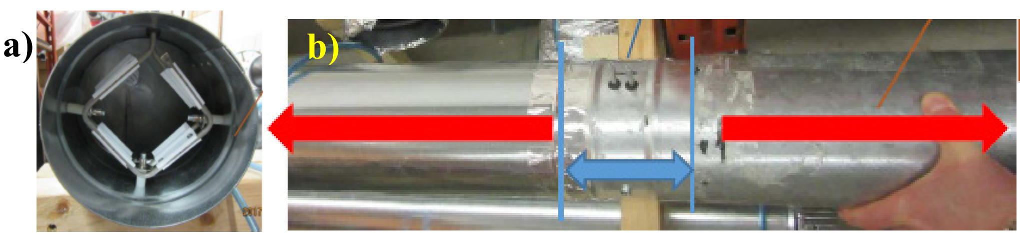


Figure 8. Venmar flow meter cross section (a), and hard duct test setup for testing (b)

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[4] Venmar is a subsidiary of Broan that manufactures this particular ERV model.
[5] Using AHRI STANDARD 1060-2013.

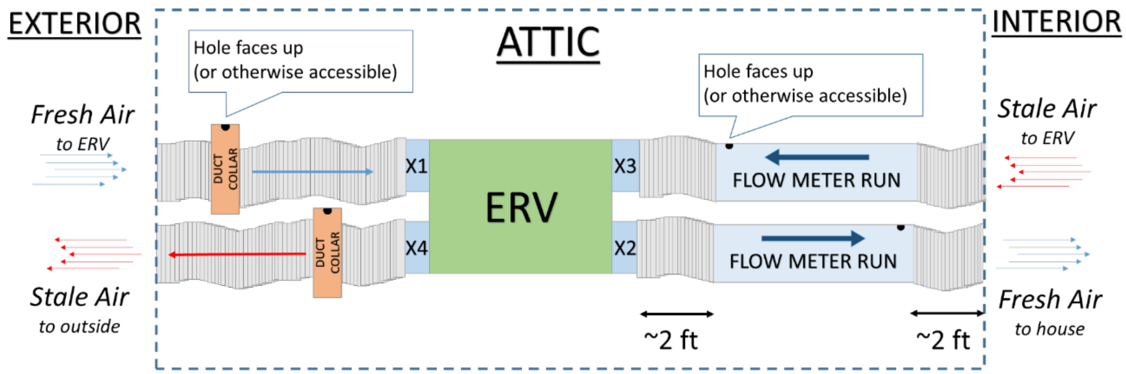

Figure 9. ERV installation diagram (holes are where T/RH probes were installed)

2.1.8 Long-Term Monitoring

2.1.8.1 Overview

Long-term monitoring lasted for 12 months after the short-term testing was completed and monitoring equipment installed. During the 12 months, the ERVs were toggled between continuous and smart operation modes on a biweekly basis. Monitoring equipment captured data at 5-minute intervals. Data included location and time-resolved energy, comfort metrics, and IAQ pollutant data measured in the home as well as occupant comfort data in the form of survey responses. Data was stored in the cloud and downloaded periodically to Southface servers.

Electrical power consumption in watts (W) was collected using current transducer (CT) monitors at the electrical panel or devices. On/off data loggers were used to record motor runtimes for all additional air-moving equipment.

All test homes included temperature and RH sensors in the attic, both floors of the living space, each of the four ERV arms, and in the AHU supply and return plenums. Additionally, one outdoor temperature and RH sensor was installed for each test home. This allowed Southface to weather-normalize data and to measure enthalpy changes between the outside and the ERVs or air handlers. Southface monitored multiple air pollutants both indoors and outdoors including PM, CO_2, and radon.

Additionally, Southface collected occupant feedback regarding their comfort using a brief three-question survey twice per season as well as an extended survey at the beginning and end of the study.

2.1.8.2 Details

Three air quality sensor packages, developed by Senseware in partnership with Southface, were placed inside each new construction home. One package containing CO_2, PM, temperature, and RH sensors was placed on each conditioned floor of a test home within a bedroom or living space area with access to an electrical outlet. Additionally, a sensor package containing a single PM sensor was placed within the kitchen in a location that would not inconvenience the residents. Finally, one radon sensor was placed within each test home on the floor of the first level. Per general practice, sensor packages were placed at least 3 ft from cooktops and ovens, at least 6 ft from exterior doors and windows opened frequently, and 2 ft from the floors and ceilings. In instances where these dimensional constraints could not be met, the research team identified the best location while paying specific attention to occupant behavior and convenience. The Southface team had six extra air quality sensor packages, so one was placed next to the existing packages (co-located) on the first and second floors of homes 1–3. This allowed analysis of precision and relative precision between co-located CO_2 and PM sensors.

One outdoor sensor package containing CO_2, PM, temperature, and RH was placed outside each test home. The optimal location for the package was considered based on safe accessibility, risk of disturbance, and protection from weather-related damage. Additionally, the location required access to a power source within range of the home's wireless network in order to remain connected to the secure mesh network platform used to remotely collect sensor data.

A visual representation of typical long-term monitoring sensor locations is mapped out in Figure 10. Each cluster of sensors only required one outlet; on/off data loggers (purple) are battery powered and do not require electrical outlet for power. All monitoring equipment was removed at the conclusion of the study.

Figure 10. IAQ sensor and ventilation performance sensor location map (typical), 1st floor (left), and 2nd floor (right)

In each test home, one T/RH sensor probe was installed within each branch of the ERV (supply from outside, supply to home, exhaust from home, and exhaust to outside). T/RH sensor probes were also placed in the air handler supply and return plenums in all homes (Figure 11). The HVAC systems were configured as zoned systems with a barometric bypass damper, so the supply T/RH probe was located upstream of the bypass damper on the supply side, and the return T/RH probe was located downstream of the bypass damper connection on the return side. T/RH were also monitored in the unfinished, vented attic space.

Figure 11. T/RH probes in the supply and return plenums of the AHU

Electrical power consumption in watts was collected using CT monitors for at least the following: whole house, air handler, ERV, A/C, and clothes dryers. All CTs installed in the electrical panel communicated with the SiteSage Gateway, which transmits data to the cloud in real time. The CT installed on the ERV communicated through the Senseware gateway to the cloud. The kitchen range hood and exhaust fans utilized on/off data loggers to monitor on/off and runtime. On/off data loggers and the radon sensor stored data internally, and the data were downloaded upon completion of the study.

Occupants from each test home were given a survey at the beginning and end of the monitoring period. The survey was based on the *Healthy Efficient New Gas Homes (HENGH) Field Study Protocol* (Chan et al. 2016). This survey can be seen in Appendix A.

Additionally, occupants from each test home were given a short, three-question survey throughout the year to determine any occupant comfort differential between the two ERV modes. The survey was given two times per season (timed so that there is one survey for each ventilation mode toggle), for a total of eight surveys per home throughout the year. The subject was not told which ERV mode they were answering questions about. This survey can be seen in Appendix A.

Southface performed a quarterly site visit for each test home in order to check on equipment, replace air handler filters, clean ERV filters, and download sensor data that were not pushed to the cloud. Air handler filters were replaced with the same minimum efficiency reporting value

(MERV) rating as those installed by the HVAC contractor (MERV 5). ERV filters were washed under lukewarm water with mild soap according to the manufacturer's instructions. Additionally, since the CO_2 sensors self-calibrate using a proprietary system called Automatic Background Calibration Logic (ABC Logic), CO_2 sensor drift was monitored by placing all sensors outside for 1 hour during this quarterly site visit.

2.1.9 Low-Cost IAQ Sensor Chamber Testing Methodology

All of the low-cost IAQ sensor packages used in the long-term monitoring study were tested both before and after the field study by UL Environment in their environmental chambers and examined for sensor drift. The tests were performed in December 2017 (6 months before House 1 started) and in December 2019 (1 month after House 4 finished). The chamber challenges were conducted in the UL Environment large chamber facility in Marietta, Georgia. The purpose of the challenges was to compare the readings of the IAQ sensors with simultaneous readings monitored with laboratory-grade instruments available at the chamber facility and check for drift of the low-cost sensors. The challenges included PM, RH, and CO_2 at several different concentration levels from material released into the chamber. Comparisons were also made for temperature, although the range of temperatures was restricted.

2.2 Data Collection Instruments and Procedures

2.2.1 Field Testing Instruments and Procedures

Electricity consumption monitoring equipment captured data at 1-min intervals, using SiteSage for Homes, for a total sample size of 525,600. The split core CT sensors have an accuracy of ±2% (rated at 10%–130% of the CTs amp rating).[6] CTs installed at the ERV used Magnelab's DCT-0016-100 split-core CT, which can detect current up to 100 amps. The CTs have an accuracy of ±2% full scale. The ERV CT also captured data at 1-min intervals.

Motor on/off data loggers were capable of 346,795 measurements, with a 512 KB memory. Data was collected in at least 3-min intervals. The logging time accuracy is within 1 min per month at 25°C.

The Venmar flowmeter has an accuracy of ±3% at 100 cfm with a pressure sensor that can measure up to 0.001-in. water column (w.c.). Southface used TEC manometer DG-700, which measures -5.0 to 5.0 in. w.c. with accuracy ±1% of the pressure reading.[7] The measurement range is 60–200 cfm.

All ventilation airflow measurements were performed once prior to the 12-month monitoring period, and then repeated following the test period in order to determine if there were changes over time. The average of the pre- and post-airflow measurements was used in the data analysis.

[6] For more information, see https://www.powerwisesystems.com/products/sitesage-energy-and-asset-management/hardware/sitesage-m.
[7] For more information, see http://energyconservatory.com/products/product/dg700/?categories=4.

All other short-term measurements were completed once, prior to the 12-month monitoring period.

The PM sensors used were PMS5003 air quality sensors developed by Plantower that can measure particle concentrations in the ranges of $PM_{0.3}$, $PM_{0.5}$, PM_1, $PM_{2.5}$, PM_5, and PM_{10}. The manufacturer-specified counting accuracy is 50% for 0.3 µm diameter particles and 98% for ≥0.5 µm diameter particles. The range for all particles sizes is 0–500 µg/m^3. These sensors also report PM mass concentration for particles smaller than 1.0, 2.5, and 10 µm. These sensors captured measurement snapshots at 5-min intervals.

The CO_2 sensors used were Telaire T6713-5K sensors designed to maintain an accuracy of ±30 ppm ±3% of reading for the life of the sensor (15 years typical). This is done through a patented self-calibration algorithm called Automatic Background Calibration Logic (ABC Logic) where the lowest value over the 7 day period is assumed to be 400 ppm. The measurement range is 0–5,000 ppm, and data was captured at 5-min intervals.

Gravimetric $PM_{2.5}$ sampling was conducted in House 1 and 2 alongside the low-cost PM sensors using Harvard Personal Exposure Monitors with 37-mm Teflon filters. Each measurement lasted 24 hours. Overall, a total of eight 37-mm Teflon filters were collected during the sampling of $PM_{2.5}$. Pre- and post-exposure weights of each filter, along with the sampling location, sampling duration (on and off time), time length, and flow rate (on and off, average) were monitored and recorded.

Temperature and RH sensors were chosen to measure indoor and outdoor air characteristics, with equivalent or higher accuracy than the temperature and RH sensors embedded in the ERVS100S. The T/RH sensors used within the IAQ sensor packages on each floor were Sensirion SHT21 sensors. The manufacturer-specified accuracy of the temperature and RH readings are ±0.54°F and ±2% of the RH reading, respectively.

The T/RH sensor probes used in the ERV ducts as well as within the AHU supply and return plenums were the Vaisala HMD112 models. These in-duct temperature and humidity probes have an accuracy of ±2% RH and ±0.36°F at 68°F, with a measurement range of 0%–100% RH and -40°–140°F.[8] In-duct temperature and humidity monitoring equipment captured data at 5-min intervals, for a total sample size of 525,600.

The radon sensor was a "homeowner"-grade model by Airthings, with a measurement range of 0–50,000 Bq/m^3 (0–1,350 pCi/L). After the first seven days, the manufacturer-specified accuracy is within 20% of the actual radon level. After one month, the accuracy is within 10% of the actual radon level. Data was collected in 24-hour intervals.

A summary table of all required sensors/equipment to conduct testing is included in Table 4.

[8] For more information, see https://www.vaisala.com/sites/default/files/documents/HMDW110-Datasheet-B211349EN.pdf.

Table 4. Summary of Equipment

Measurement	Equipment
Data Acquisition	Senseware Online Platform
PM	Plantower PMS5003
CO_2	Telaire T6713-5K
Radon	Airthings Wave Radon Sensor
Gravimetric $PM_{2.5}$ Daily Average Reference Measurement	Harvard Personal Exposure Monitor
Indoor and Outdoor Temperature and RH	Sensirion SHT21
Envelope Air Leakage	The Energy Conservatory Blower (TEC) Door Apparatus and TECTITE Software
Duct Leakage	TEC Duct Blaster Apparatus and TECBLAST Software
Air Handler Airflow Rates	TEC TrueFlow Air Handler Flow Meter
Electrical Energy Consumption	SiteSage for homes CTs, ≤14 (50-amp and 20-amp split core sensors) Magnelab DCT-0010-005 split-core CT for ERV
On/Off Data Logger Exhaust Fan Runtime	On/off data loggers for exhaust fans and range hood Onset UX90-004M on/off logger
Local Exhaust Airflow Rates Bathroom fans, dryer exhaust, kitchen range hood, etc.	Powered Flow Hood (outlet terminal) and exhaust fan flow meter (inlet terminal)
ERV Ventilation Temperature and RH	Vaisala HMD112 in-duct Temperature and Humidity Probe. Quantity: 4 (ERV)
Supply and Return Plenum Temperature and RH	Vaisala HMD112 in-duct Temperature and Humidity Probe. Quantity: 2 (supply, return)
Ventilation Airflow	Primary method: Venmar Flow Meter
	Secondary method: Alnor LoFlo Balometer

2.2.2 Low-Cost IAQ Sensor Chamber Testing Instruments and Procedures

The devices were tested in an environmental chamber for chemical emissions in order to test for drift throughout the year-long field experiment. The challenges were conducted in a 25.7 m^3 chamber, supplied with purified air at a rate of 1.0 air change per hour. The environmental chambers were operated by Nick Sutton of UL Environment in 2017 and by Elliott Horner of UL Environment in 2019.

Environmental chamber operation and control measures used in this study meet the requirements of ISO 16000-9[9] and ASTM D 6670.[10] The chambers used are manufactured from inert materials. Supply air to the chamber is stripped of formaldehyde, volatile organic compounds, and other contaminants, so that any contaminant backgrounds present in the empty chamber fall below strict levels (<10 µg/m³ total volatile organic compounds, <10 µg/m³ total particles, <2 µg/m³ formaldehyde, <2 µg/m³ for any individual volatile organic compounds). UL chambers are process controlled and equipped with a continuous data acquisition system for verification of the operating conditions of airflow, temperature, and humidity.

Aerosol was generated for the PM challenge by burning a stick of incense in the chamber. This generated an aerosol of fine PM that increased over the period of combustion. After the combustion ended, the concentration of PM followed a decay typical of source removal (or extinguishment) when a chamber is continuously supplied with 1 ACH of clean air. After the peak and subsequent decay of the aerosol concentration, a second burn of one half of a stick of incense was conducted.

The increase and subsequent decay of PM concentration provided multiple concentration levels for comparison. Four times were selected at several concentration levels. The concentration values over an 11-min period were averaged at each concentration level. During the PM "dosing" with incense smoke, PM was recorded with an aerosol monitor and with a laser particle counter.

In 2017, attempts were made to generate differences in RH using the humidified air supply to the chamber. The humidification system in the air supply is designed to maintain stable conditions, however, so the differences seen were not large. Several points in the RH midrange are available for comparison, but the range of RH levels seen in the field was not represented. As with the PM challenge, four intervals were selected with different RH levels. The values are averages of 11-min periods with the indicated time at the midpoint of the period.

In 2019, RH differences were generated by operating two cool mist ultrasonic humidifiers in the chamber to drive the humidity to near saturation. An earlier effort to lower the RH by supplying the chamber with dry air did not lower the humidity enough to provide meaningful differences in RH. As with the PM challenge, four intervals were selected with different RH levels. The values are averages of 11-min periods with the indicated time at the midpoint of the period.

[9] ISO 16000-9: "Indoor air—Part 9: Determination of the emission of volatile organic compounds from building products and furnishing—Emission test chamber method."
[10] ASTM D 6670: "Standard Practice for Full-Scale Chamber Determination of Volatile Organic Emissions from Indoor Materials/Products."

Differences in CO_2 concentration were generated by releasing CO_2 from a compressed gas cylinder into the chamber. Intervals were selected at five different concentration levels. The average of an 11-min period is presented with the corresponding midpoint time.

2.2.2.1 Particles ($PM_{2.5}$ and PM_{10} mass)

Continuous particle monitoring was performed using a TSI Model 8533 DustTrak Aerosol Monitor, calibrated with Arizona road dust. These monitors use a 90° light scattering measurement to continuously determine airborne particle concentrations over time. The Model 8533 simultaneously measures particles of 2.5 micrometers and smaller in size ($PM_{2.5}$) and 10 micrometers and smaller in size (PM_{10}). The analytical range of this instrument is 0.005 to 150 mg/m³.

2.2.2.2 Particles (3 micrometer and 10 micrometer counts)

Continuous particle count concentrations were monitored with a TSI Model 9306 AeroTrak portable particle counter. These monitors are laser particle counters that simultaneously monitor six size channels over time. The analytical range extends to 2.1E+8 particles / m3.

2.2.2.3 Carbon Dioxide, Temperature, and Relative Humidity

CO_2 was measured continuously with a TSI Model 7575X QTrak with a model 982 IAQ probe. The monitor has an effective quantitation range of 1–5,000 ppm for CO_2 with an accuracy of ±3%. The QTrak has an accuracy for RH of ±3% and ±0.5°C for temperature. Additional humidity measurements were made with datalogging Onset Hobo thermo-hygrometers.

2.3 Analysis Methods

2.3.1 Comfort Data Analysis

The following analysis was performed in order to answer **Research Question 1:**

Does a recently developed smart ventilation algorithm that considers outdoor temperature and RH in a market-ready ERV create a more acceptable indoor environment, expressed qualitatively as occupant comfort and quantitatively through indoor T/RH measurements, compared to continuous operation of that ERV in humid climates?

To answer this question, the occupant comfort survey data were analyzed and compared between ERV modes and to IAQ and T/RH data between those two modes. To account for the fact that a major determining factor of IAQ is the activities of the individuals within the homes, analyses were aimed at comparing the ERV modes *within* each home, rather than comparing one home to another. Trends within each test home could then be compared to other test homes to see if they were consistent.

Using the Get Psyched plugin[11] for Excel, indoor T/ RH measurements were used to calculate the dewpoint at every time step throughout the year, assuming atmospheric pressure at sea level. Temperature, RH, and dewpoint data for each sensor within each house was then averaged by

[11] For more information, see: https://www.kw-engineering.com/psychrometrics/.

ERV mode both annually and by season to determine the effect of ERV mode on these comfort metrics. To calculate whole-home average comfort metrics, the temperature, RH, and dewpoint data for the upstairs and downstairs sensors were averaged within each home.

Additionally, the percentage of time above certain humidity thresholds was calculated. Originally, the ASHRAE 55 threshold of 62.2°F dewpoint was chosen, but this was lowered to 55°F because 62.2°F was not exceeded enough to provide a good comparison between modes. The RH comfort threshold chosen was 60% RH.

Similar analyses to the above calculations were also performed on the outdoor T/RH data. Additional analyses that shed light on this first research question concerned ERV behavior, ERV performance, and A/C behavior. Descriptions of these analyses can be seen in Section 2.3.3.2: Ventilation Performance Analysis.

2.3.2 IAQ Data Analysis

The following analysis was performed in order to answer **Research Question 2:**

Using low-cost IAQ sensors whose performance has been independently verified, is there a discernable difference between measured indoor air pollutants when comparing continuous and smart ERV operation modes?

The team used descriptive statistics and mixed regression modeling to examine associations between the measured indoor air pollutants and corresponding ERV operational modes. Specifically, multivariate linear mixed regression modeling was conducted to assess factors that affect the temporal variability in the concentrations of each pollutant in the test homes. The general form of the model can be expressed as:

$$\text{Pollutant level}_{ist} = \beta_1 \text{ERV Mode}_{ist} + \beta_2 Z_{ist} + \theta_{it} + \varepsilon_{ist}$$

where $\text{Pollutant level}_{ist}$ denotes the hourly concentration of air pollutant $'i'$ measured at house $'s'$ during hour $'t'$. Here, $'s'$ indexes each of the four homes. $'\beta_1'$ is the coefficient for the differential impact of the ERV smart mode on hourly concentration of air pollutant $'i'$ compared to the continuous ERV mode. $'\beta_2'$ is the coefficient for factor Z_{st} including outdoor $PM_{2.5}$ concentrations, microenvironment (i.e., first floor, second floor, kitchen), indoor temperature, and humidity. These factors were included in the models simultaneously. The Z-parameters were selected, a priori, as factors that may also explain indoor pollutant concentrations beyond ERV mode, selected based on numerous previous studies showing that they impact the indoor air pollution levels. They were included in the model primarily as a means of controlling for these factors to better understand the impact of ERV mode. Finally, $'\theta_t'$ denotes the sampling date-specific random intercepts used to capture potential variations in each sampling dates not explained by $'Z_{st}'$ and ε_{st} represents residual normally distributed random error.

Summary statistics and box plots were also generated to report the overall distribution of the air pollutant data measured at each of the four homes during the study period. All statistical analyses were completed in R, version 3.3.1.[12]

IAQ data from each home were merged into a single data set, and missing values were replaced with "NA." For tested sites with pairs of side-by-side sensors (Houses 1–3), absolute and relative precision were calculated and included as part of the data quality assurance/quality check (QAQC) report. Mean air quality concentrations were calculated for those side-by-side measurements that passed the QAQC analysis. All raw IAQ data were sampled at 5-min intervals and were averaged at the hourly level for all IAQ analyses. The final analytic data set totaled 12,235 hourly IAQ observations on 151 variables.

2.3.2.1 In-Situ Gravimetric $PM_{2.5}$ Monitor Comparison Analysis

Gravimetric $PM_{2.5}$ data from the Harvard Personal Exposure Monitors were analyzed as follows:

For each filter, the total $PM_{2.5}$ mass (in µg) was calculated using the following equation:

Total $PM_{2.5}$ mass = Mean off-weight (post sample collection) - Mean on-weight (pre sample collection)

For each filter, the $PM_{2.5}$ concentration (in $\mu g/m^3$) was calculated using the following equation:

$PM_{2.5}$ concentration=Total $PM_{2.5}$ mass/(Mean flow rate * Sampling duration) *1000

Where:

- Mean flow rate was read from the data-logger (pre-calibrated) *unit: L/minute*
- Sampling duration = (Off-time) – (On-time) *unit: minutes*

Limit of detection (LOD) estimates for the $PM_{2.5}$ mass concentrations measured using the Personal Exposure Monitors were derived as three times the standard deviation of eight 37-mm Teflon filter field blanks, and the LOD was 1.8 mg/m^3.

Absolute and relative precision of the co-located low-cost sensors were calculated as part of a data QAQC analysis through root-mean-square deviation (RMSD). RMSD is used to compare differences between two things that may vary, neither of which is accepted as the "standard." Hence, it has been used widely to find the average difference between side-by-side measurements between instruments. In this analysis, when measuring the average difference in measured concentrations between two side-by-side instruments, the formula becomes:

$$\mathrm{RMSD} = \sqrt{\frac{\sum_{t=1}^{T}(x_{1,t} - x_{2,t})^2}{T}}.$$

[12] More information on the R Foundation for Statistical Computing can be found at: http://www.r-project.org/.

where, $x_{1,t}$ denotes the pollutant levels measured by instrument #1 at time point 1, and $x_{2,t}$ denotes the pollutant levels measured by instrument #2 at time point 1.

2.3.2.2 Low-Cost IAQ Sensor Chamber Testing Analysis

Summary statistics were compiled for the array of sensors at each chamber challenge point. These included maximum reading, minimum reading, and average of the group. The statistical comparisons included calculating the coefficient of variation (CV) and relative percent difference (RPD). The CV was calculated for the group of sensors at each challenge point to assess the variation among the individual sensors in the array. The RPD was used to assess the difference between the average of the sensors and the reference value from the laboratory instrument. RPD values were also calculated for the individual sensors and the reference value.

The CV characterizes the variability within a set of measurements. It is calculated as the standard deviation of a group of measurements divided by the average of those measurements, expressed as a percent. This is also referred to as the relative standard deviation.

The RPD is used to compare the spread between two measurements. It is calculated as the absolute value of the difference between the two measurements divided by the average of the two measurements, expressed as a percent. Both CV and RPD are smaller if the data values are closer together. As measures of closeness of values, 20% or below is generally regarded as acceptable for both CV and RPD.

2.3.3 Energy Data Analysis

The following analysis was performed in order to answer **Research Question 3:**

How much space-conditioning energy is saved and how accurately can BEopt models (with customized time-varying ventilation scripts) predict HVAC energy savings for test homes switching between smart and continuous operation modes?

Southface monitored HVAC and whole-house energy consumption as well as ERV and heating/cooling supply and return air T/RH so as to determine variables such as induced latent and sensible load and ERV effectiveness. Energy measurements were compared to the BEopt model created with customized time-varying ventilation scripts to evaluate the model’s accuracy.

All psychrometric calculations were performed using the Get Psyched plugin,[13] assuming all pressures are at atmospheric pressure at sea level.

2.3.3.1 HVAC Energy Analysis and BEopt Comparison

Actual HVAC and whole-house energy consumption as well as ERV energy consumption was recorded and totaled for the year and for each month. This was compared to the BEopt models created with customized time-varying ventilation scripts on an annual and monthly basis to evaluate the models’ accuracy.

[13] For more information, see: https://www.kw-engineering.com/psychrometrics/.

The BEopt models produced some unexpected inaccurate results when modeling the ERVs, so the results presented in the body of the report are corrected using external engineering calculations. The raw BEopt results and the corrections are detailed in Appendix D.

For direct comparison to the BEopt models, metered A/C condensing unit energy usage was weather-normalized on a daily basis to the Charleston Intl AP (TMY3) weather data using actual and TMY heating degree days and cooling degree days (base 65). It was also regressed against the ERV mode for each day (using a 1 for smart or 0 for continuous mode). This allowed the metered daily A/C energy data recorded during each ERV mode toggle to be extrapolated to an entire year for whole-year A/C energy usage comparison.

For comparison to BEopt models, the metered ERV energy usage was extrapolated to a whole year assuming that the percentage of time in standby, as monitored during smart mode periods, was representative of the entire year. The wattage while in standby varied slightly by house but was around 5 W. The wattage while ventilating also varied slightly for each house, but was around 100 W. The actual average wattage for each ERV was used for the calculations and whole-year extrapolations.

2.3.3.2 Ventilation Performance Analysis

Southface analyzed ERV performance and HVAC system performance across all four seasons. Real-world performance data of ERVs, especially in hot and mixed-humid climate zones, is scarce and vital to informing manufacturer and builder decision-making regarding the appropriate use of this technology. Field-confirmed relative exposure calculations were completed for each home and compared to calculations based on TMY weather data.

To understand the performance of the ERV system, Southface collected data at four key points in the ERV airstreams. Figure 12 shows how two main airstreams, the supply and exhaust entering and leaving the house, interact with the unit. All airstreams entering the ERV are labeled as *inlet*, and all airstreams leaving the ERV are labeled as *outlet*. This results in four points of interest where Southface installed T/RH probes to record measurements, labeled as X_1, X_2, X_3, and X_4. The temperature and RH at each air measurement station were used to calculate the enthalpy at each location and the ERV effectiveness as described in the following section (ERV Effectiveness).

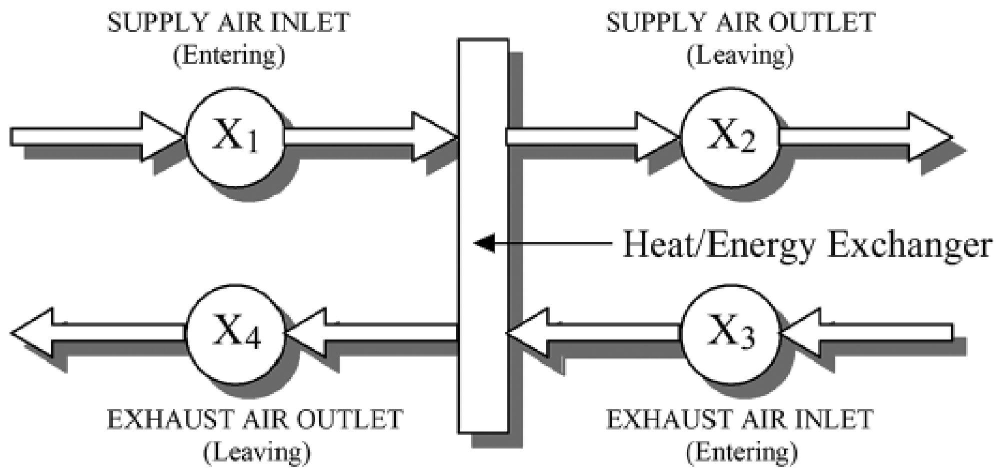

Figure 12. Airstream measurement stations X_1, X_2, X_3, and X_4 on the ERV system

Additional T/RH probes were placed at the AHU supply and return plenums for all homes. These data were used to determine the sensible and latent loads of the air conditioner and were compared to the loads induced by the ERV.

The following equations were used to determine the sensible, latent, and total enthalpies for each of the four ERV measurement stations. The same calculations were made with the data from the AHU supply and return plenums.

ERV Effectiveness Analysis

In-field ERV performance was described in terms of sensible, latent, and total effectiveness (ε), defined as the ability to transfer energy from one airstream to another over the range of specified operating conditions. ANSI/ASHRAE Standard 84 (Method of Testing Air-to-Air Heat/Energy Exchangers) provides the necessary analytical foundation and field test methods (ASHRAE 2013). Two separate effectiveness ratios may be calculated for each of the three measures of interest: one for the supply airstream and one for the exhaust airstream. The supply ratios were calculated at every 5-min timestamp according to the following equations.

Occasionally, these effectiveness calculations resulted in unreasonable values at timestamps when the indoor and outdoor temperatures and humidity ratios were similar to each other. In these cases, the measurement error of the T/RH sensors (see Section 2.2) could result in an effectiveness that was greater than 1 or less than 0. The effectiveness values at these timestamps were left out of the seasonal and annual average calculations.

The general equation for thermal effectiveness is:

$$\varepsilon = \frac{heat\ rate}{thermodynamic\ maximum\ heat\ rate}$$

For sensible energy changes in heat exchangers, this may be represented by the following equation:

$$\varepsilon_s = \frac{sensible\ energy\ exchange\ rate}{maximum\ sensible\ energy\ exchange\ rate}$$

$$\varepsilon_s = \frac{C\Delta T\ (from\ one\ airstream\ flow)}{C_{min}\Delta T\ (from\ one\ airstream\ inlet\ to\ the\ other)}$$

where C is the thermal capacity rate for either the supply (C_2) or exhaust (C_3) airstream, depending on the effectiveness calculated, and C_{min} is the minimum of the two thermal capacity rates. This may be further expanded to the following:

$$\varepsilon_s = \frac{\dot{m}c_{pa}\Delta T\ (from\ one\ airstream\ flow)}{(\dot{m}c_{pa})_{min}\Delta T\ (from\ one\ airstream\ inlet\ to\ the\ other)}$$

where c_{pa} is the specific heat of dry air and $\dot{m}$ is the mass flow rate of the airstream. Within the normal operating conditions for the ERV, the specific heat of dry air does not change significantly. Therefore, the *sensible effectiveness* (also called apparent effectiveness) for the supply airstream and the exhaust airstream may be simplified as follows:

$$\varepsilon_{s,supply} = \frac{\dot{m}_2\ (T_1 - T_2)}{(\dot{m}_{2,3})_{min}(T_1 - T_3)}$$

$$\varepsilon_{s,exhaust} = \frac{\dot{m}_3\ (T_4 - T_3)}{(\dot{m}_{2,3})_{min}(T_1 - T_3)}$$

where $\dot{m}_2$ and $\dot{m}_3$ are mass flows at stations 2 and 3, and T_1, T_2, T_3 and T_4 are temperatures at stations 1, 2, 3, and 4.

Similar equations may be used to compare the latent energy and total energy transfer performance of the ERV. The latent energy effectiveness may be described by the following two equations:

$$\varepsilon_{l,supply} = \frac{\dot{m}_2\ h_{fg}(W_1 - W_2)}{(\dot{m}_{2,3}h_{fg})_{min}(W_1 - W_3)}$$

$$\varepsilon_{l,exhaust} = \frac{\dot{m}_3 h_{fg}\ (W_4 - W_3)}{(\dot{m}_{2,3}h_{fg})_{min}(W_1 - W_3)}$$

where h_{fg} represents the latent heat of evaporation of water, and W represents the humidity ratio at the appropriate measurement station. In addition, h_{fg} is considered to be constant throughout the typical ERV operating conditions, and the equations are further reduced to these for *latent effectiveness*:

$$\varepsilon_{l,supply} = \frac{\dot{m}_2\ (W_1 - W_2)}{(\dot{m}_{2,3})_{min}(W_1 - W_3)}$$

$$\varepsilon_{l,exhaust} = \frac{\dot{m}_3(W_4 - W_3)}{(\dot{m}_{2,3})_{min}(W_1 - W_3)}$$

By assuming h_{fg} is constant throughout the testing conditions, this equation will introduce an error of much less than 1% relative to the energy change calculations that include latent heat rates.

Finally, the *total energy effectiveness* is defined as follows:

$$\varepsilon_{t,supply} = \frac{\dot{m}_2\ (h_1 - h_2)}{(\dot{m}_{2,3})_{min}(h_1 - h_3)}$$

$$\varepsilon_{t,exhaust} = \frac{\dot{m}_3\ (h_4 - h_3)}{(\dot{m}_{2,3})_{min}(h_1 - h_3)}$$

where h is the total enthalpy at the appropriate measurement station.

Total, Sensible, and Latent Induced Load Analysis

Sensible, latent, and total enthalpy at each measurement station were calculated using measured temperature and RH values to determine the ventilation load supplied to each test home. The calculations were performed during steady-state conditions after ventilators had been operating for least 10 min. Long-term field measured values for temperature and RH as well as short-term airflow measurement values were recorded for use in the following equations, adapted from ASHRAE Fundamentals 2009 (ASHRAE 2009).

The heat rate at the supply air outlet (station X_2) is considered the load into the house from the ERV and will be a heating or cooling load depending on the season. The heat rate at the exhaust air inlet (station X_3) is considered the load removed from the house by the ERV. The difference between the heat rate at X_2 and X_3 is the "net" or "induced" load caused by the ERV system on the house.

The induced sensible, latent, and total loads ($Q_{induced}$, in Btu/minute) and induced water vapor flow rate ($\dot{m}_{w,induced}$, in lbs_w/minute) by the ERV were calculated for every 5-min timestamp using the following equations:

$$Q_{t,induced} = \frac{\dot{m}_2 \cdot h_2}{v_2} - \frac{\dot{m}_3 \cdot h_3}{v_3}$$

$$\dot{m}_{w,induced} = \dot{m}_2 \cdot W_2 - \dot{m}_3 \cdot W_3$$

$$Q_{l,induced} = 1053.71 \cdot \dot{m}_{w,induced}$$

$$Q_{s,induced} = Q_{t,induced} - Q_{l,induced}$$

where $\dot{m}_n$ is the measured airflow rate (cfm), v_n is the specific volume of air (ft^3/lb_{da}), h_n is the specific enthalpy (Btu/lb_{da}), and W_n is the humidity ratio (lb_w/lb_{da}) at each measurement station n.

The latent load was assumed to be the net water vapor flow rate times the heat of evaporation at 70 deg F (1053.71 Btu/lb_w). The induced loads and vapor flow rates were then converted to Btu/hr and lbs/hr, respectively.

In houses where the ERV installation was such that the exhaust airflow from the house was greater than the supply airflow to the house ($X_3 > X_2$), thus putting the house under net negative pressure, the net difference between the two airflows (X_3 - X_2) was assumed to come from outdoors at the local outdoor air conditions as measured by the outdoor sensor package. This load was added to the induced load calculation with the total induced load considered the "actual" induced load and an "ideal" induced load being the load if the supply and exhaust airflows were balanced ($X_3 = X_2$).

AHU Condensation Rate Analysis

The original intent for capturing T/RH data in the supply and return plenums of the AHU (Figure 11) was to be able to calculate the sensible, latent, and total loads of the A/C system as well as the condensation rate. However, the HVAC system was configured as a two-zone system with a zone controller, two zone dampers, and a barometric bypass damper. This configuration only permitted the measurements necessary for the condensation rate calculation because the airstream flow rate through the bypass damper was unknown, as was the return air T/RH prior to the mixing of the bypass damper airstream.

The condensation rate due to the A/C operation was performed using the AHU constant mass electronically commutated motor blower flow rate, as well as the calculated humidity ratio at the supply and return (post-bypass damper mixing) plenums using equation (44) in *ASHRAE Fundamentals 2009* (ASHRAE 2009):

$$\dot{m}_{w,condensed} = \dot{m}_{AHU}\left(W_{return} - W_{supply}\right)/v_{return}$$

where $\dot{m}_{AHU}$ is the AHU airflow rate (cfm), v is the specific volume of air (ft^3/lb_{da}), and W is the humidity ratio (lb_w/lb_{da}) at the supply or return. The resulting condensation rate was then able to be converted to lbs_w/hr and $gallons_w$/hr.

Two additional assumptions were that condensation was only occurring when the A/C condenser was running and that condensation rates would only be positive in value, because all homes set their thermostat fan to "auto" rather than "continuous." Thus, for every 5-min timestamp, this calculation was performed when the recorded condenser power at that timestamp was >0 and when the resulting $\dot{m}_{w,condensed}$ was positive in value.

3 Results

3.1 Home Performance Results

Below are several tables with the as-measured characteristics of the HVAC equipment and test homes in general. All homes were located within a 700-ft radius in the same neighborhood in Charleston, South Carolina, with construction completed in 2018.

Table 5. Test Home General Characteristics

	House 1	House 2	House 3	House 4
# Bedrooms	4			
# Baths	3	3	4	4
Master Bedroom Location	2nd Floor	1st Floor	1st Floor	1st Floor
Orientation	NW	SSW	SSW	NNE
# Residents	2	4	4	3
# Animals	1 cat	2 cats	none	1 dog
Total Square Footage	2,391	2,300	2,227	2,300
First Floor	1,218	1,307	1,299	1,307
Second Floor	1,173	993	928	993
Data Start Date	6/29/2018 at 11 a.m.	11/2/2018 at 11 a.m.	9/28/2018 at 11 a.m.	11/16/2018 at 11 a.m.
Typical Thermostat Settings	Fan: Auto Summer: 76 day/72 night Winter: 70	Fan: Auto Summer: 74 day/68 night Winter: 68-70, depending on comfort	Fan: Auto Summer: 75 Winter: 68	Fan: Auto Summer: 74 Winter: 74

Table 6 shows the test home envelope leakage and ventilation characteristics measured as described in Section 2.1.7. As a note, the range hoods in Houses 3 and 4 were both over-the-range microwave/range hood units with ducted exhaust, whereas Houses 1 and 2 had independent range hoods.

Table 6. Test Home Envelope and Ventilation Performance Characteristics

	House 1	House 2	House 3	House 4
Blower Door Results				
CFM_{50}	1,637	1,762	1,853	1,482
ACH_{50}	4.33	4.87	5.30	4.10
Duct Blaster Results				
Duct Blaster Total Leakage (CFM_{25})	156	222	223	242
Duct Blaster Total Leakage ($CFM_{25}/100ft^2$)	6.5	9.7	10.0	10.5
Duct Blaster Leakage to Outside (CFM_{25})	75	74	93	82
Duct Blaster Leakage to Outside ($CFM_{25}/100ft^2$)	3.1	3.2	4.2	3.6
Exhaust Fan Flow Meter Results				
Bath Fan 1 (Master Bath Shower)	46 cfm	65 cfm	61 cfm	0 cfm (Not functioning)
Bath Fan 2 (Master Bath Toilet)	18 cfm	42 cfm	43 cfm	46 cfm
Bath Fan 3 (1st Floor Hallway)	55 cfm	56 cfm	50 cfm	49 cfm
Bath Fan 4 (2nd Floor Hall)	13 cfm	52 cfm	52 cfm	59 cfm
Bath Fan 5 (2nd Floor Bedroom)	N/A	N/A	54 cfm	55 cfm
Range Hood (Low/Med/High)	103/171/210 cfm	108/150/195 cfm	29 cfm	47/60/72 cfm

Table 7 shows the test home ERV characteristics. Airflow in arms 2 and 3 were measured both before the 12-month monitoring period (pre) and after the 12-month monitoring period (post). The average of the pre and post was used in the comfort, IAQ, and energy analyses. As installed, the ERVs were all unbalanced to some extent, with Houses 1, 2, and 4 net negative and House 3 net positive.

The EATR was the same for all ERVs, calculated in Venmar's lab at 95 cfm. ERV vent locations for each house are also specified below. All ERVs were located in the vented attic of each home.

Table 7. Test Home ERV Characteristics

	House 1	House 2	House 3	House 4
Filter	Washable MERV 7 at ERV core supply and exhaust			
Predicted ERV continuous airflow requirements, per ASHRAE 62.2-2016 (using 2,300 ft^2 area, 4 bedrooms, and 4 ACH_{50})				
Predicted Q_{tot} requirement (cfm)	106.5			
Predicted Q_{fan} requirement (cfm)	60.6			
Actual ERV continuous airflow requirements, per ASHRAE 62.2-2016 (using actual area, bedrooms, and measured ACH_{50})				
Actual Q_{tot} requirement (cfm)	109.2	106.5	104.3	106.5
Actual Q_{fan} requirement (cfm)	58.0	51.4	46.3	60.1
As-measured ERV airflows				
ERV Supply (X_2) Average CFM	**92.96**	**84.48**	**99.89**	**97.66**
ERV Supply (X_2) Pre CFM	93.05	85.84	99.16	98.74
ERV Supply (X_2) Post CFM	92.87	83.13	100.63	96.58
ERV Return (X_3) Average CFM	**111.33**	**99.31**	**91.63**	**108.32**
ERV Return (X_3) Pre CFM	111.40	100.09	90.94	110.47
ERV Return (X_3) Post CFM	111.26	98.53	92.33	106.18
ERV-Induced Infiltration Flow	-18.37 cfm	-14.83 cfm	+8.26 cfm	-10.66 cfm
EATR (%)	4.4%			
ERV Vent Locations				
ERV OA Intake (X_1)	Soffit	Soffit	Attic Wall	Attic Wall
ERV Supply (X_2)	AHU Return	Upstairs Hallway	Upstairs Hallway	Upstairs Hallway
ERV Return (X_3)	Upstairs Hallway			
ERV Exhaust (X_4)	Soffit	Soffit	Attic Wall	Soffit

Next are the test home furnace and A/C system characteristics. All total external static pressure readings (TESP) were within the 0.1–0.8" w.c. range specified in the AHU manual, so total flow rates used were the heating and cooling flow rates specified for the constant mass flow electronically commutated motor at the field-observed control board dip-switch settings.

Table 8. Test Home HVAC System Characteristics

	House 1	House 2	House 3	House 4
Filter	MERV 5, installed at return grilles			
# Zones	2 (one upstairs and one downstairs)			
# Returns	4 (two upstairs and two downstairs)			
Orientation	Upflow			
Location	Second floor utility closet			
Configuration	Split system A/C and condensing furnace			
Duct Location	Primarily the vented attic			
Heating Mode				
Air-Conditioning, Heating, and Refrigeration Institute (AHRI) Furnace Output	96,000 Btu/hr			
AHRI Heating Annual Fuel Utilization Efficiency	96.1%			
Heating CFM	1,870 cfm (0.1–0.8" w.c. TESP)			
Heating Supply Static Pressure	0.34" w.c.	0.41" w.c.	0.40" w.c.	0.44" w.c.
Heating Return Static Pressure	-0.46" w.c.	-0.29" w.c.	-0.23" w.c.	-0.30" w.c.
Heating Total External Static Pressure	0.80" w.c.	0.70" w.c.	0.63" w.c.	0.74" w.c.
Cooling Mode				
AHRI Cooling Output	34,171 Btu/hr			
AHRI Cooling SEER	15 SEER			
AHRI Cooling EER	12.5 EER			
Cooling CFM	1,736 cfm (0.1–0.8" w.c. TESP)			
Cooling Supply Static Pressure	0.23" w.c.	0.26" w.c.	0.28" w.c.	0.27" w.c.
Cooling Return Static Pressure	-0.42" w.c.	-0.22" w.c.	-0.18" w.c.	-0.22" w.c.
Cooling Total External Static Pressure	0.65" w.c.	0.48" w.c.	0.46" w.c.	0.49" w.c.

3.2 Comfort Analysis Results

3.2.1 Comfort Metric Results

The annual averages of the comfort metrics for each house can be seen in Table 9. The displayed values are the averages of the upstairs and downstairs T/RH sensors in each home, except House 4, which only uses the upstairs sensor because the downstairs sensor had an incomplete data set with 21% missing. In both modes, the annual average RH is below 55% for all 4 homes. It is worth noting that both of these tested modes supplied the houses with significantly more outside air than the minimum requirements (Table 7 compared to Table 33), and yet reasonable RH levels were able to be maintained. The annual average temperature is very similar for both modes within each house which means, on an annual basis, the sampling was relatively even.

Although there is not a significant difference in average RH in any house, all houses have a lower RH in smart mode than continuous mode. All houses also have a lower percentage of time above 60% RH in smart mode compared to continuous mode, with the difference being quite significant in Houses 2 and 3. This trend makes intuitive sense, as the ERV control logic responds to the peaks in outdoor humidity, and thus limits the peaks in humidity that are brought indoors. Evidently, though, this limiting effect was not enough to significantly affect the average RH.

Table 9. Test Home Annual Average Indoor Comfort Metrics

	Comfort Metric	Continuous Mode	Smart Mode
House 1	Temperature	71.4	72.3
	RH	50.0	49.6
	% of time above 60% RH	0.40%	0.06%
House 2	Temperature	72.3	72.4
	RH	53.2	52.8
	% of time above 60% RH	13.09%	6.33%
House 3	Temperature	73.1	73.0
	RH	54.2	53.6
	% of time above 60% RH	21.42%	14.29%
House 4	Temperature	75.0	75.3
	RH	48.9	48.8
	% of time above 60% RH	0.77%	0.48%

Table 10 shows how the ERVs operated in each mode on an annual basis. Houses 2–4 had similar smart mode behavior, being triggered into standby 12%–15% of the time. However, House 1 was in standby around 10% of the time. This makes sense in light of the fact that, due to a difference in testing period start date, House 1 experienced a different summer than the other houses. The average water vapor flow[14] induced by the operation of the ERVs in each home (Section 3.4.2) shows that smart mode's behavior does reduce the amount of moisture compared to continuous mode.

[14] Across all hours, not just hours of operation.

Table 10. Test Home Annual ERV Operation

	Metric	Continuous Mode	Smart Mode
House 1	% Time in standby	0%	9.9%
	Average induced water vapor flow rate (lbs/hr)	0.99	0.81
House 2	% Time in standby	0%	14.7%
	Average induced water vapor flow rate (lbs/hr)	0.61	0.52
House 3	% Time in standby	0%	12.9%
	Average induced water vapor Flow rate (lbs/hr)	0.50	0.35
House 4	% Time in standby	0%	11.5%
	Average Induced Water Vapor Flow rate (lbs/hr)	0.56	0.53

Table 11 displays the annual average weather data recorded by T/RH sensors outside each home. The data show that, on an annual basis, the mode toggling periods were not biased toward lower humidity during smart mode except for in House 4. Despite this, all houses still had lower indoor average RH and percent time over 60% RH in smart mode.

Table 11. Test Home Annual Average Weather Data

	Comfort Metric	Continuous Mode	Smart Mode
House 1	Temperature	71.6	72.0
	RH	71.2	71.3
	% of time above 60% RH	77.07%	77.21%
	Dewpoint	61.7	62.2
House 2	Temperature	71.0	71.7
	RH	71.6	72.8
	% of time above 60% RH	70.72%	73.96%
	Dewpoint	59.7	61.4
House 3	Temperature	71.1	70.2
	RH	71.9	72.2
	% of time above 60% RH	79.76%	80.46%
	Dewpoint	61.0	60.3
House 4	Temperature	70.3	72.3
	RH	73.1	72.2
	% of time above 60% RH	81.86%	75.53%
	Dewpoint	61.7	62.4

Factoring out temperature in each house, the annual averages of the indoor dewpoint metrics can be seen in Table 12. There is not a significant difference in *average* dewpoint in any house, nor is there a consistent directionality between modes. However, there is a consistently lower percentage of time above 55°F dewpoint for all houses in smart mode compared to continuous mode, with the difference being most significant in Houses 2 and 3. These trends are similar to Table 9, where the percentage of time above 60% RH was lower in smart mode for all houses, with Houses 2 and 3 being most significant.

Table 12. Test Home Annual Average Indoor Dewpoint Metrics

	Metric	Continuous Mode	Smart Mode
House 1	Dewpoint	51.8	52.3
	% of time above 55°F dewpoint	21.21%	21.02%
House 2	Dewpoint	54.2	54.2
	% of time above 55°F dewpoint	47.98%	42.45%
House 3	Dewpoint	55.5	55.1
	% of time above 55°F dewpoint	64.54%	61.43%
House 4	Dewpoint	54.3	54.6
	% of time above 55°F dewpoint	48.32%	46.34%

The results become more unexpected when looking at the seasonal averages of the metrics for each house (Table 13).[15] Once again, these are the averages of the upstairs and downstairs T/RH sensors in each home, except for House 4, which only uses the upstairs sensor.

Like the annual averages, seasonally no house exceeded an average of 55% RH in either smart or continuous mode except for House 3, which averaged 55.8% RH in continuous mode in the summer and 55.1% RH in smart mode in the fall. So, both continuous and smart modes appear to be effective at providing outside air while maintaining reasonable average indoor humidity levels. Once again, it is worth noting that both of these tested modes supplied the houses with significantly more outside air than the minimum requirements (Table 7 compared to Table 33).

The unanticipated result was that the only season where the comfort metrics are directionally consistent between houses is winter, where all four houses have lower average RH readings and lower percentages of time above 60% RH in smart mode compared to continuous mode. Every other season has at least one house where the RH and percentage of time above 60% RH are not directionally consistent with each other or consistent with the ERV mode. This trend is maintained when examining the dewpoint metrics as well (Table 14).

It was expected that smart mode would cease ventilation most often in the summer and least often in winter (Table 37), resulting in proportional differences in indoor humidity between modes for those seasons. Although the smart mode ERV behavior (percentage of time in standby, Table 16) was in line with the expected behavior, the opposite result seems to have occurred: directionally inconsistent humidity levels in all houses for each season *except* winter. The lack of a consistent difference and directionality between modes in all seasons besides winter was initially perplexing but became more clarified when viewed in light of the A/C behavior in each home. This is examined in detail next.

[15] Seasonal definitions: spring is 3/20–6/28, summer is 6/29–9/21, fall is 9/22–12/20, and winter is 12/21–3/19.

Table 13. Test Home Seasonal Average Indoor Comfort Metrics

		Spring		Summer		Fall		Winter	
	Comfort Metric	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**
House 1	Temperature	72.1	73.0	73.8	73.1	70.7	74.0	69.2	69.0
	RH	48.3	49.6	50.9	51.7	50.3	48.4	50.5	48.8
	% of time above 60% RH	0.03%	0.14%	0.07%	0.08%	0.24%	0.01%	1.25%	0.00%
House 2	Temperature	73.1	73.8	74.6	74.5	71.1	70.8	70.6	70.5
	RH	51.8	53.3	53.2	52.7	53.0	55.3	54.6	50.1
	% of time above 60% RH	2.92%	4.95%	1.26%	1.94%	16.89%	14.13 %	31.30%	4.29%
House 3	Temperature	73.1	74.0	73.8	74.5	73.0	71.4	72.6	72.2
	RH	53.3	54.8	55.8	54.6	54.6	55.1	53.1	49.9
	% of time above 60% RH	15.07%	10.05%	39.80%	34.21%	15.66%	11.33 %	15.13%	1.56%
House 4	Temperature	74.8	75.4	75.6	75.7	74.2	75.1	75.2	75.0
	RH	47.9	49.6	53.0	52.1	49.3	50.7	45.2	42.6
	% of time above 60% RH	0.26%	0.05%	0.25%	0.96%	2.26%	0.90%	0.31%	0.00%

Table 14. Test Home Seasonal Average Indoor Dewpoint Metrics

		Spring		Summer		Fall		Winter	
	Metric	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**
House 1	Dewpoint	51.5	53.0	54.5	54.3	51.3	53.2	49.9	48.9
	% of time above 55°F dewpoint	14.04%	25.19%	37.17%	34.11%	16.03%	16.51%	17.62%	8.26%
House 2	Dewpoint	54.3	55.7	56.4	56.1	52.9	53.9	53.3	50.9
	% of time above 55°F dewpoint	44.75%	55.62%	64.82%	59.48%	37.29%	37.36%	45.07%	17.34 %
House 3	Dewpoint	55.0	56.6	56.9	56.9	55.6	54.5	54.4	52.4
	% of time above 55°F dewpoint	58.13%	82.15%	86.72%	87.24%	61.98%	51.45%	51.32%	24.89 %
House 4	Dewpoint	53.7	55.3	57.3	57.0	53.8	55.5	52.3	50.7
	% of time above 55°F dewpoint	47.56%	63.01%	92.80%	90.38%	50%	59%	39.74%	14.80 %

The average weather data during each mode toggle in every season can be seen in Table 15. Also included for comparison is the weather from the local weather station. It appears that the proximity of the T/RH sensors to the houses may have some effect on the sensed temperatures when compared to the weather station data. This was further examined and appears to be confirmed when the T/RH data is compared with the ERV OA data in Section 3.5. It is worth noting that the house monitoring periods were staggered, so House 1 experienced a different summer from the rest. Additionally, Houses 1 and 3 experienced a different fall than Houses 2 and 4.

The purpose of examining the following weather data is to check the uniformity of the weather between ERV operation modes. The average outdoor RH tracks directionally with the outdoor percentage of time above 60% RH in all cases. This is unlike the indoor comfort metrics where the RH and percentage of time above 60% RH are not directionally consistent or consistent with the ERV mode in every season except winter.

Additionally, note that the outdoor dewpoint was higher on average during smart mode in the spring in all four houses. It was also higher on average in continuous mode in the winter. The summers were similar between modes and the falls varied by house.

Table 15. Test Home Seasonal Average Weather Data

		Spring		Summer		Fall		Winter	
	Comfort Metric	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**
House 1	T	75.7	76.7	84.3	84.1	66.1	67.8	60.0	59.3
	RH	65.6	72.8	75.3	74.7	73.9	71.1	69.8	66.6
	% of time above 60% RH	65.61%	78.94%	88.46%	87.02%	81.17%	77.32%	73.05%	65.55%
	Dewpoint	63.5	67.3	75.7	75.3	57.6	58.2	50.2	48.2
House 2	T	72.2	75.6	83.8	82.6	68.26	71.09	59.63	57.39
	RH	66.2	74.1	73.9	76.6	73.14	72.27	73.08	68.00
	% of time above 60% RH	53.95%	69.24%	87.99%	92.39%	71.61%	72.99%	69.34%	61.23%
	Dewpoint	59.6	66.3	75.6	75.2	53.2	58.1	50.4	46.2
House 3	T	74.7	75.4	84.4	82.9	66.0	64.8	59.5	57.5
	RH	65.6	73.4	74.3	76.0	75.4	72.3	72.2	67.2
	% of time above 60% RH	67.89%	81.59%	87.90%	92.00%	86.43%	80.66%	76.83%	67.57%
	Dewpoint	61.6	65.7	75.0	74.4	57.6	55.3	49.8	45.9
House 4	T	74.4	75.1	83.6	82.2	61.9	68.9	61.4	62.9
	RH	66.5	73.8	77.1	78.4	75.1	76.1	73.8	60.6
	% of time above 60% RH	68.68%	81.42%	92.53%	93.16%	84.60%	76.90%	81.65%	50.63%
	Dewpoint	65.5	66.0	75.4	74.6	53.5	60.8	52.3	48.2
Local Weather Station	T	71.6	72.8	80.8	80.1	61.9	62.5	55.1	54.5
	RH	70.2	76.6	81.4	83.1	82.1	80.3	78.0	73.6
	% of time above 60% RH	68.72%	81.35%	95.76%	95.95%	87.79%	87.40%	79.39%	71.83%
	Dewpoint	60.1	64.2	74.2	74.1	55.9	55.8	47.1	45.0

In order to investigate the unexpected comfort metric trends, we examined the ERV operation data. Pertinent ERV operation data can be seen in Table 16. A more complete ERV performance data analysis can be found in Section 3.4.

As discussed in Section 3.4, the ERV's behavior in smart mode was very similar to what the BEopt model predicted. Namely, in smart mode, standby was triggered most in the summer, second most in spring, third most in fall, and seldom in winter in three of the four houses. As mentioned above, House 1 experienced a different summer than the other three, so it had different smart mode behavior.

Also displayed in Table 16 are the average induced water vapor flow rates[16] due to the operation of the ERV. The induced water vapor flow rates are lower in smart mode for every house in every season, except House 2 and House 4 in the fall. Notably, the flow rate is negative in smart mode in every home during the winter, meaning on average there is a net flow of water vapor out of the house due to the operation of the ERV.

When these ERV-induced water vapor flow rates are compared with the average condensation rates due to the A/C operation[17] (Table 17), it becomes evident that the magnitude of the condensation rate is likely obscuring any effect that the difference in ERV modes is having. The ratio of A/C condensation rate to induced water vapor flow rate ranges from about 2x to more than 10x during the cooling season (spring through fall in Charleston) for each of the houses.[18] During the heating season (winter), when the A/C ran very little, the ERVs also averaged net negative latent loads. This means that during the heating season both the ERV and A/C averaged a small net removal of moisture from the houses.

There was a lower average A/C condensation rate in smart mode for all houses in every season (except House 1 in spring), indicating that the indoor humidity in smart mode was not preferentially aided over continuous mode by the operation of the A/C. Additional data on the sensible and latent loads induced by the ERV can be seen in Table 42 and Table 43.

Note that due to a malfunction of the electricity monitoring equipment, House 2 annual and House 4 fall condensation rates were unable to be calculated.

[16] Across all hours, not just hours of operation. The average condensation rate during operation is around 0.9 gallons/hr for every house, which is in line the output of the MeasureQuick app for similar conditions and in line with the (Guz 2005) generalization of 0.2 gallons/hr/ton (0.6 gallons/hr for these systems).
[17] Across all hours, not just hours of A/C operation.
[18] Large amounts of moisture were removed by the A/C and only a small fraction was from the ERV, so the question arises as to where the rest of the moisture was coming from. Although a full moisture mass balance was not performed as part of this study, our suspicion is that most of the moisture is from both forced and natural infiltration through the building envelope in the extremely humid environment of Charleston. Any operation of bath fans, range hood, or even the AHU (through duct leakage to the outside) will induce infiltration that adds to the latent load. As a point of reference, 50 cfm of untempered outside air in Charleston in July adds about 3.75 lbs/hr (0.45 gallons/hr) of moisture.

Table 16. Test Home Seasonal ERV Operation

		Spring		Summer		Fall		Winter	
	Metric	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**
House 1	% time in standby	0%	18.4%	0%	7.6%	0%	11.3%	0%	2.3%
	Average induced water vapor flow rate (lbs/hr)	1.01	0.94	2.23	1.99	0.65	0.39	0.06	-0.08
House 2	% time in standby	0%	24.4%	0%	21.3%	0%	9.3%	0%	3.8%
	Average induced water vapor flow rate (lbs/hr)	0.60	0.53	1.57	1.19	0.35	0.54	-0.07	-0.17
House 3	% time in standby	0%	22.2%	0%	16.1%	0%	11.0%	0%	2.5%
	Average induced water vapor flow rate (lbs/hr)	0.53	0.49	1.47	1.18	0.22	0.00	-0.21	-0.29
House 4	% time in standby	0%	21.9%	0%	11.4%	0%	9.3%	0%	3.5%
	Average induced water vapor flow rate (lbs/hr)	0.62	0.56	1.67	1.37	0.06	0.40	-0.11	-0.20

Table 17. Test Home A/C Condensation Rate

		Spring		Summer		Fall		Winter	
	Metric	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**
House 1	Average A/C condensation rate (lbs/hr)	1.90	2.08	5.44	5.19	1.60	1.17	0.41	0.20
	Ratio of condensation rate to ERV induced water vapor flow rate	189%	221%	244%	261%	246%	299%	700%	-261%
House 3	Average A/C condensation rate (lbs/hr)	3.90	3.76	7.55	6.27	2.11	1.34	0.26	0.11
	Ratio of condensation rate to ERV induced water vapor flow rate	741%	767%	512%	531%	957%	33,550 %	-126%	-38%
House 4	Average A/C condensation rate (lbs/hr)	3.46	3.29	5.80	5.33	N/A	N/A	0.37	0.13
	Ratio of condensation rate to ERV induced water vapor flow rate	562%	585%	348%	390%	N/A	N/A	-336%	-65%

Indoor humidity is a function of the interaction between the ERV, A/C, weather, ventilation fan usage, and occupant activities such as showers, cooking, etc. Smart mode appeared to reduce the average RH and % of time above 60% RH on an annual basis, but seasonally the effect was inconsistent, and the results are inconclusive as to whether the seasonal variations are attributable to the ERV mode, the A/C operation, or one of the other unmonitored factors.

3.2.2 Comfort Survey Results

The responses from the seasonal surveys issued to each homeowner can be seen in Table 18. Only Houses 1 and 2 responded to every survey. Occupants were neutral, satisfied, or very satisfied with "general comfort" and "air quality" in all responses except for House 4 in the spring in smart mode. Unfortunately, there was not a continuous mode survey result with which to compare this to see if the mode was a factor, if it was seasonal, or something else. Overall, there was no discernable difference in either occupant satisfaction or perception of humidity between smart and continuous mode in the survey responses.

Table 18. Test Home Comfort Survey Results

		Spring		Summer		Fall		Winter	
	Question	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**
House 1	General comfort?	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Neutral
	Air quality (odors, stuffiness, allergens)?	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Satisfied	Neutral
	Humid or dry?	Neutral	Neutral	Dry	Neutral	Dry	Neutral	Neutral	Dry
House 2	General comfort?	Satisfied	Satisfied	Very Satisfied	Very Satisfied	Very Satisfied	Satisfied	Neutral	Neutral
	Air quality (odors, stuffiness, allergens)?	Satisfied	Satisfied	Satisfied	Satisfied	Very Satisfied	Satisfied	Satisfied	Satisfie d
	Humid or dry?	Neutral	Fluctuate d	Humid	Humid	Neutral	Neutral	Neutral	Neutral
House 3	General comfort?	N/A	Very Satisfied	N/A	Very Satisfied	N/A	Very Satisfied	N/A	N/A
	Air quality (odors, stuffiness, allergens)?	N/A	Satisfied	N/A	Very Satisfied	N/A	Very Satisfied	N/A	N/A
	Humid or dry?	N/A	Very Dry	N/A	Dry	N/A	Dry	N/A	N/A
House 4	General comfort?	N/A	Neutral	Satisfied	Satisfied	N/A	N/A	N/A	N/A
	Air quality (odors, stuffiness, allergens)?	N/A	Unsatisfi ed	Satisfied	Satisfied	N/A	N/A	N/A	N/A
	Humid or dry?	N/A	Neutral	Neutral	Very Dry	N/A	N/A	N/A	N/A

3.2.3 Comfort Results Summary

Research Question 1: Does a recently developed smart ventilation algorithm that considers outdoor temperature and RH in a market-ready ERV create a more acceptable indoor environment, expressed qualitatively as occupant comfort and quantitatively through indoor T/RH measurements, compared to continuous operation of that ERV in humid climates?

Conclusion: The smart ventilation algorithm under consideration in this field test did create a more acceptable indoor environment on an annual basis as quantitatively measured through T/RH readings, expressed most discernably as "percentage of time above 60% RH" and "percentage of time above 55°F dewpoint." However, the difference it made was inconsistent during the spring, summer, and fall months, and only directionally consistent during the winter months. We suspect that this is primarily due to the long runtimes and concomitant dehumidification activity of the A/C units in response to the high sensible loads in Charleston. Necessary for this result, and for the reasonable RH levels maintained in each house, is for the average sensible heat ratio of the equipment to be lower than that of the load, which highlights the importance of proper HVAC commissioning. The effect of the smart ventilation algorithm was not discernable to the occupants in this study, as recorded through seasonal surveys.

3.3 IAQ Analysis Results

3.3.1 Statistical Results

The key IAQ indicator species measured at the test homes were $PM_{2.5}$, PM_1, PM_{10}, and CO_2. Measurements were made at 5-min intervals and averaged to hourly levels for all IAQ analyses.

For Houses 1–3, a pair of side-by-side IAQ sensor packages were installed at two of the indoor sampling locations. This allowed absolute and relative precision to be calculated as part of a data QAQC analysis using root-mean-square deviation (RMSD). As shown in Table 19, the low-cost sensors had mean estimates of absolute and relative precision for $PM_{2.5}$ of 2.1 ug/m^3 and 21.3%, respectively; PM_1 absolute and relative precision of 1.24 ug/m^3 and 18.1%, respectively; PM_{10} absolute and relative precision of 3.23 ug/m^3 and 30.1%, respectively; and CO_2 absolute and relative precision of 65.7 ppm and 10.7%, respectively. The second floor “Device A” CO_2 sensor in House 1 was the major outlier; it drifted wildly throughout the 12-month monitoring.

These results show that the low-cost PM and CO_2 sensors generally have good agreement with each other.

Table 19. QAQC on Co-Located Sensors (PM in ug/m³ and CO_2 in ppm)

Pollutant	House	Micro-environment	Device A (avg. ± std. dev.)	Device B (avg. ± std. dev.)	Absolute Precision	Relative Precision
$PM_{2.5}$	House 1	First Floor	7.2 ± 10	8.4 ± 10.4	1.6	20.8%
	House 2		10.2 ± 17.3	9.7 ± 18	1.6	16.2%
	House 3		11.5 ± 14.7	13 ± 16.8	2.2	17.8%
	House 1	Second Floor	7.7 ± 8.9	7.7 ± 8.8	1.6	21.1%
	House 2		9.3 ± 17.6	9.5 ± 16	3.4	35.9%
	House 3		12.3 ± 16.2	12.7 ± 16.8	2.0	16.2%
PM_1	House 1	First Floor	5.4 ± 7.2	6.2 ± 7.4	1.1	19.4%
	House 2		7.3 ± 10.6	6.6 ± 10.7	1.3	18.3%
	House 3		8 ± 8.9	9.2 ± 9.8	1.3	14.8%
	House 1	Second Floor	5.8 ± 6.6	5.6 ± 6.2	1.2	22.0%
	House 2		6.7 ± 10	6.8 ± 9.7	1.5	22.3%
	House 3		8.7 ± 9.2	9 ± 9.3	1.0	11.5%
PM_{10}	House 1	First Floor	7.6 ± 10.8	8.9 ± 11.5	1.9	22.8%
	House 2		11 ± 20.1	10.4 ± 20.5	1.7	15.6%
	House 3		13 ± 19	14.4 ± 22	3.0	22.1%
	House 1	Second Floor	8.7 ± 10.9	8.1 ± 9.6	3.0	35.6%
	House 2		10.8 ± 25	10.5 ± 19.6	6.1	57.1%
	House 3		13.6 ± 20.8	13.9 ± 22.8	3.7	27.2%
CO_2	House 1	First Floor	522.1 ± 104.5	534.1 ± 112.8	13.7	2.6%
	House 2		649.4 ± 182.9	666.2 ± 186.7	24.6	3.7%
	House 3		681.2 ± 215.5	672.9 ± 210.4	11.3	1.7%
	House 1	Second Floor	654.2 ± 456.6	570.1 ± 119.2	317.2	51.8%
	House 2		561.9 ± 143.7	565.5 ± 142.6	15.9	2.8%
	House 3		566.1 ± 151.5	575.7 ± 156.7	11.5	2.0%

The summary statistics for indoor and outdoor PM_1, $PM_{2.5}$, PM_{10}, and CO_2 can be seen in Table 20 through Table 23. In instances where two co-located sensors where available (as seen in Table 19) the average of the two sensors was used, excluding House 1 second floor CO_2 where one of the sensors had errors. Box plots of the data can be seen in Figure 13 through Figure 16. Circles within the boxplots indicate the averages.

Overall, House 4 had the highest average indoor PM concentrations across different microenvironments during the study period, while House 1 had the lowest average levels. None of the average outdoor or indoor IAQ metrics exceeded current National Ambient Air Quality Standard (NAAQS) 24-hour average thresholds. The annual primary threshold for $PM_{2.5}$ was exceeded slightly inside Houses 3 and 4, but the annual secondary threshold for $PM_{2.5}$ was not exceeded in any house.[19]

Mean pollutant concentrations of PM_1, $PM_{2.5}$, and PM_{10} measured at the outdoor sites were lower than the indoor sites across all houses except for House 1. PM concentrations were comparable between all indoor and outdoor sites for House 1 and House 2, while the indoor concentrations were significantly higher than those measured at the outdoor sites at House 3 and House 4, indicating elevated indoor emission sources at these two houses. Indoor levels of CO_2 were consistently higher compared to outdoor levels for all four houses. Levels of all the measured air pollutants did not seem to differ significantly across the three indoor microenvironments. For each house, the location of the microenvironment monitored is listed in this order: outdoor, first floor location, second floor location, kitchen.

Table 20. Summary Statistics for PM_1 Hourly Concentrations by House and by Microenvironment (ug/m³)

House	Microenvironment	N	Mean	Std. dev.	Median	Min	Max
House 1	Outdoor	8221	6.9	5.4	5.6	0	74
	Living Room	8790	5.8	7.3	4.4	0	192.8
	M. Bedroom	8050	5.7	6.4	4.2	0	111.5
	Kitchen	9083	5.7	6.9	4.3	0	190.1
House 2	Outdoor	10214	6.2	11.3	4.5	0	286.3
	M. Bedroom	10275	6.9	10.6	4.8	0	248.6
	Living Room	9583	6.8	10	4.8	0	264.2
	Kitchen	10343	7.2	10.6	5.1	0	230
House 3	Outdoor	9049	5.8	7.8	4.3	0	213.7
	M. Bedroom	9052	8.6	9.3	6.3	0	158.2
	Living Room	8861	8.9	9.2	6.7	0	163.2
	Kitchen	9240	8.3	9.8	5.9	0	199
House 4	Outdoor	7804	5.5	5	4	0	65.3
	M. Bedroom	8959	8.3	11.2	5.2	0	169.8
	Living Room	10515	9.7	14	6.2	0	278.2
	Kitchen	10425	10.1	13.9	6.8	0	288.1

[19] The primary and secondary thresholds for $PM_{2.5}$ are 12 ug/m³ and 15 ug/m³, respectively, on a yearly average, or 35 ug/m³ for 24-hour average. For more information, see https://www.epa.gov/criteria-air-pollutants/naaqs-table.

Table 21. Summary Statistics for $PM_{2.5}$ Hourly Concentrations by House and by Microenvironment (ug/m^3)

House	Microenvironment	N	Mean	Std. Dev.	Median	Min	Max
House 1	Outdoor	8237	8.9	7.2	7	0	101.8
	Living Room	8803	7.8	10.1	5.8	0	258.8
	M. Bedroom	8039	7.7	8.8	5.7	0	147
	Kitchen	9083	7.6	9.8	5.6	0	257.9
House 2	Outdoor	10216	9.4	27.3	6	0	921.8
	M. Bedroom	10275	9.9	17.6	6.6	0	591
	Living Room	9584	9.5	17.2	6.3	0	526.2
	Kitchen	10343	10	16.8	6.7	0	514.8
House 3	Outdoor	9049	8.7	17.4	6	0	538.8
	M. Bedroom	9052	12.2	15.8	8.5	0	501.5
	Living Room	8861	12.5	16.5	9	0.2	549.9
	Kitchen	9240	12.1	16.6	8.3	0	530.7
House 4	Outdoor	7788	7.6	7.1	5.5	0	111.1
	M. Bedroom	8959	12.1	17.4	7.2	0	283.8
	Living Room	10531	13.7	22.1	8.3	0	692.2
	Kitchen	10487	15	16.3	11.8	0.1	291.7

Table 22. Summary Statistics for PM_{10} Hourly Concentrations by House and by Microenvironment (ug/m^3)

House	Microenvironment	N	Mean	Std. Dev.	Median	Min	Max
House 1	Outdoor	7633	9.8	8	7.6	0	115
	Living Room	8803	8.3	11.1	6	0	269.1
	M. Bedroom	8050	8.4	10.1	6	0	177.8
	Kitchen	9083	8.2	11.2	5.9	0	312.5
House 2	Outdoor	10217	10.4	36.6	6.4	0	1178.7
	M. Bedroom	10275	10.7	20.3	6.9	0	764.8
	Living Room	9584	10.8	23.1	6.9	0	838.2
	Kitchen	10343	10.8	19.3	7	0	620.6
House 3	Outdoor	9049	9.4	21.8	6.4	0	753.2
	M. Bedroom	9052	13.7	20.4	9.2	0	818.2
	Living Room	8861	13.8	21.7	9.5	0.2	894.3
	Kitchen	9240	13.6	21.4	9.1	0	839.4
House 4	Outdoor	7804	7.9	7.6	5.8	0	122.5
	M. Bedroom	8942	13.1	19.5	7.6	0	302.5
	Living Room	10531	15.2	26	8.9	0	923.7
	Kitchen	10421	15.6	25.6	9.5	0	928.7

Table 23. Summary Statistics for CO_2 Hourly Concentrations by House and by Microenvironment (ppm)

House	Microenvironment	N	Mean	Std. Dev.	Median	Min	Max
House 1	Outdoor	8659	441.3	27.8	436.7	376.3	605.6
	Living Room	9089	528.1	108.5	510.7	374.7	2153.5
	M. Bedroom	8025	612.0	250.4	562.7	222.6	3625.8
House 2	Outdoor	9624	453.4	43.8	447.2	333.0	883.6
	M. Bedroom	10274	657.3	184.0	631.1	308.1	2381.9
	Living Room	10492	563.7	142.8	530.2	343.8	1851.4
House 3	Outdoor	9072	457.1	38.7	451.9	316.3	849.9
	M. Bedroom	9073	677.1	212.8	646.3	343.0	2060.0
	Living Room	9139	570.9	154.0	539.6	356.1	1684.4
House 4	Outdoor	8998	497.1	114.6	461.5	242.0	1768.1
	M. Bedroom	8966	642.2	200.6	609.5	266.5	1783.2
	Living Room	10536	584.5	155.7	558.0	245.5	1940.9

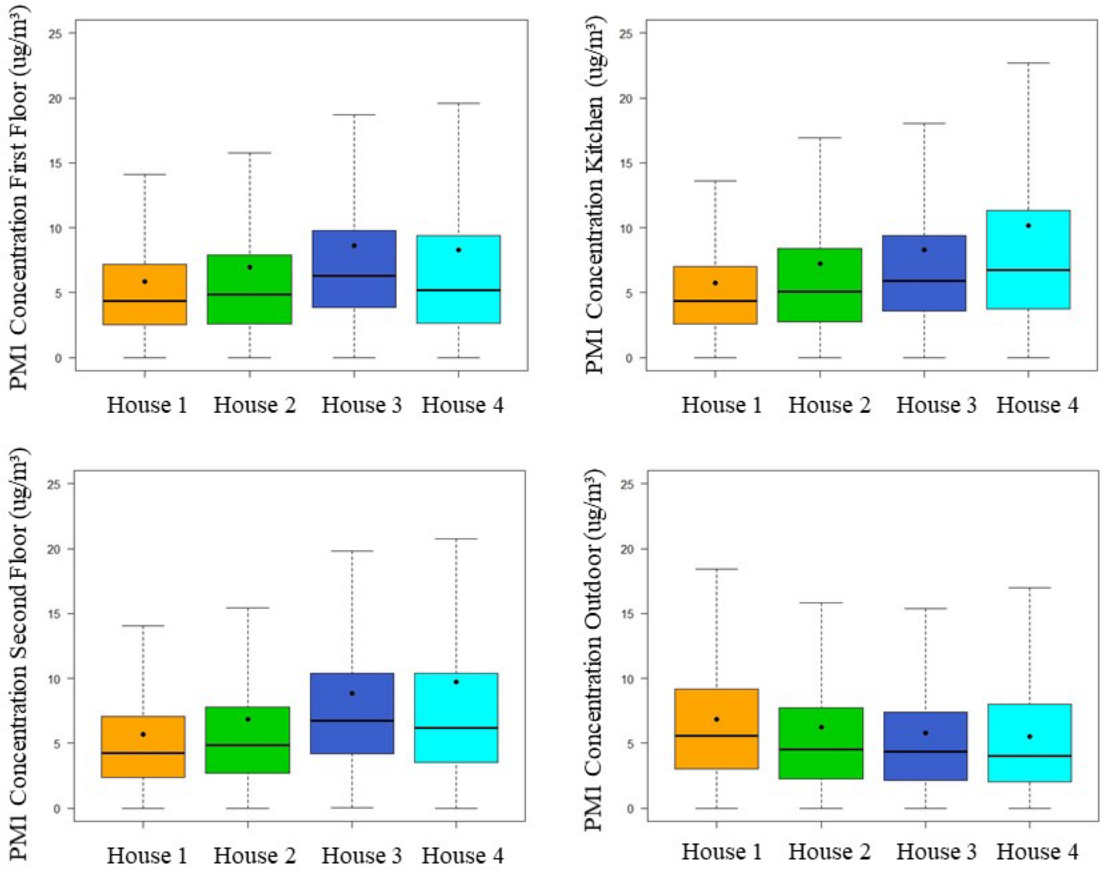

Figure 13. Boxplot of PM_1 concentrations in different microenvironments

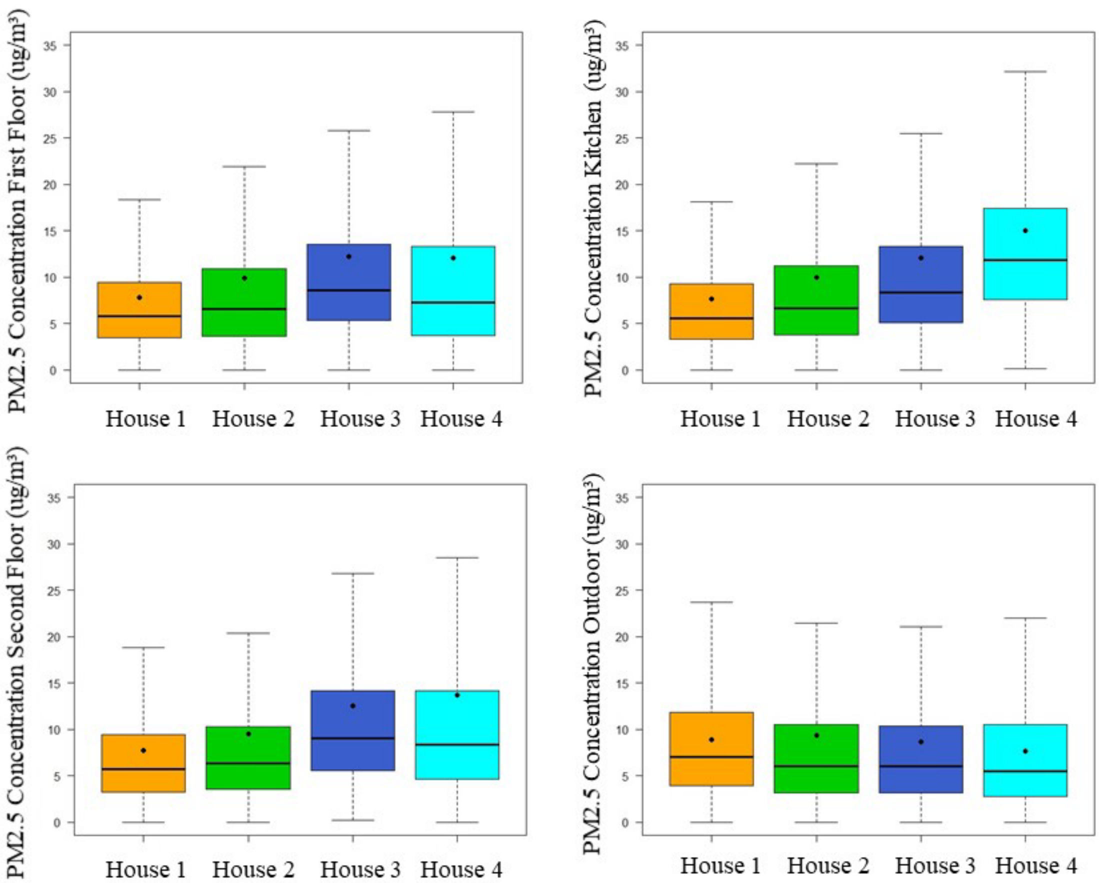

Figure 14. Boxplot of $PM_{2.5}$ concentrations in different microenvironments

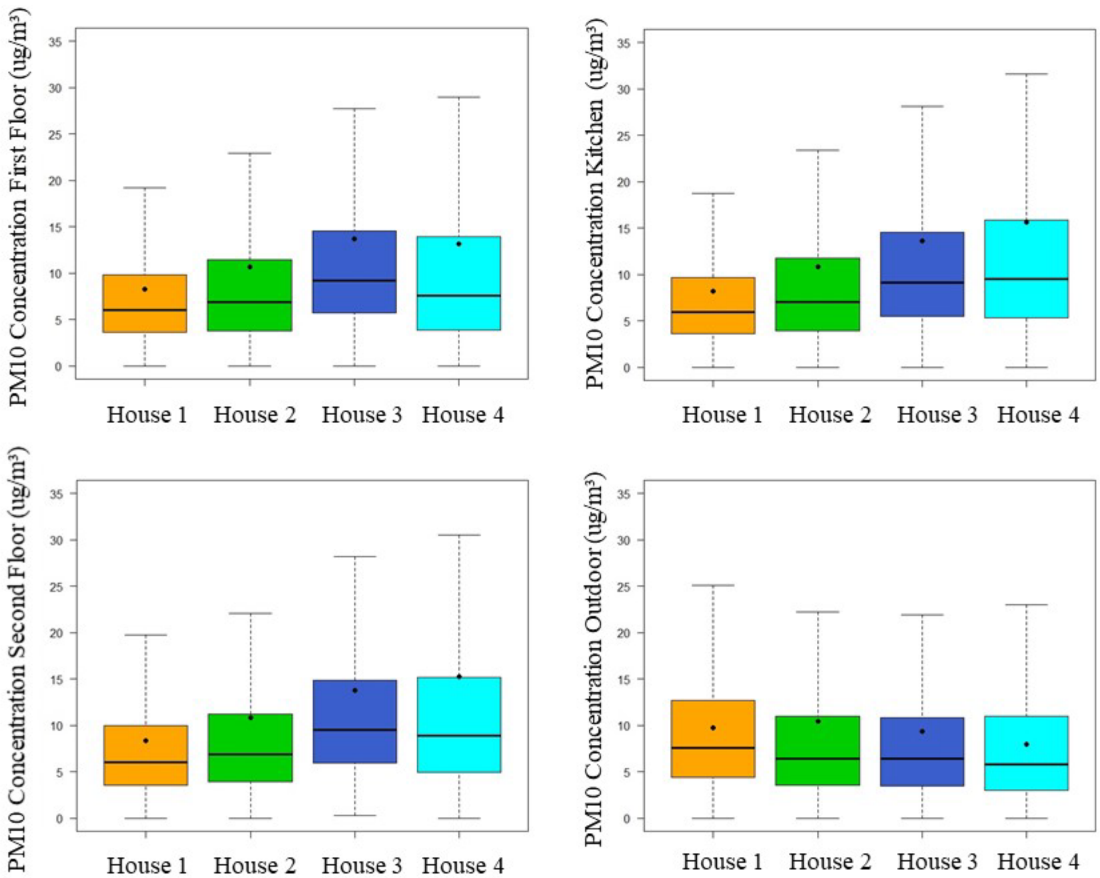

Figure 15. Boxplot of PM_{10} concentrations in different microenvironments

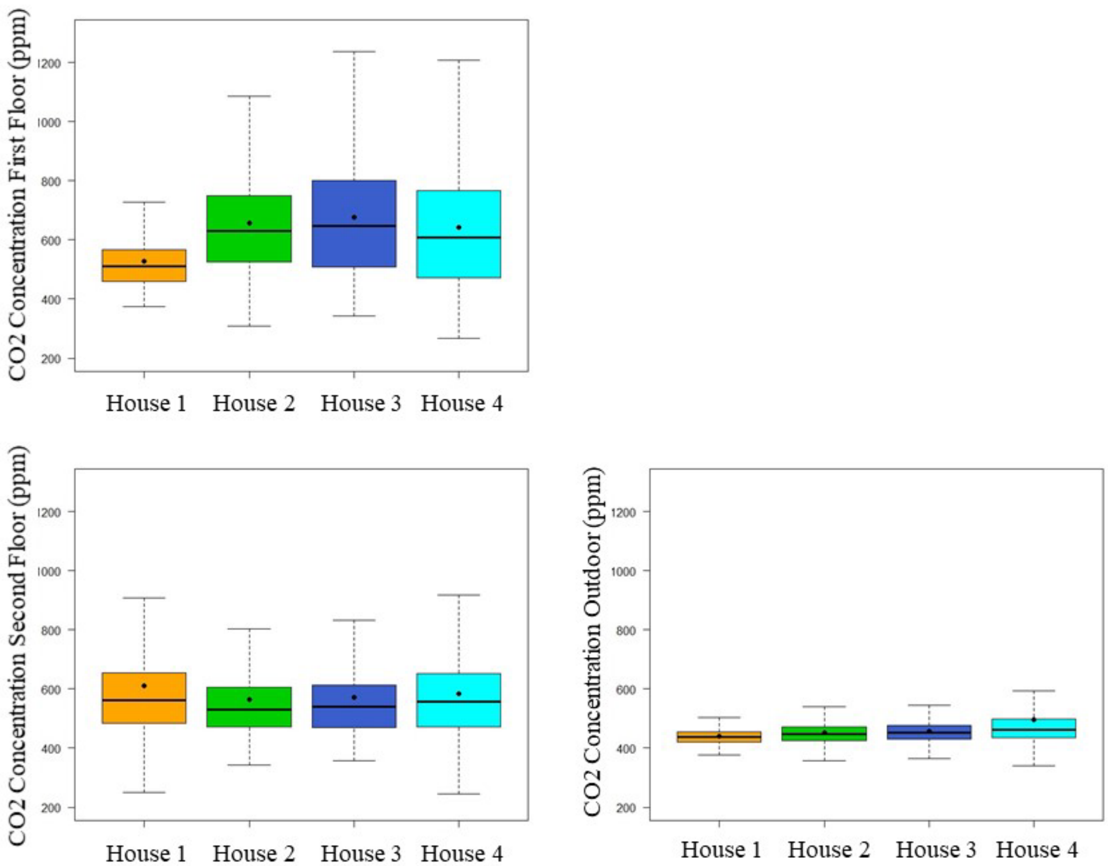

Figure 16. Boxplot of CO_2 concentrations in different microenvironments

As shown in Figure 17 through Figure 21, there were lower (albeit comparable) median levels of $PM_{2.5}$ in smart mode compared to continuous mode. Similar trends can be seen for PM_1 and PM_{10} in Appendix B. However, as seen in the figures and in Table 24, the mean values of $PM_{2.5}$ were directionally inconsistent between houses and microenvironments when comparing smart mode to continuous. Differences also varied in statistical significance according to t-test results.

Indoor median CO_2 was slightly lower in continuous mode versus smart mode in all four houses for all microenvironments (see Figure 20 and Figure 21). However, differences were small, and levels were mostly comparable between modes. Mean CO_2 was also slightly lower in continuous mode for all houses and microenvironments, except for the second floor of House 1. This is tabulated in Table 25 where all indoor differences between modes are shown to be statistically significant according to t-test results. These results are consistent with the fact that more ventilation occurred in continuous mode than smart mode, because smart mode has periods when the ERV is in standby (see Table 33 and Table 34).

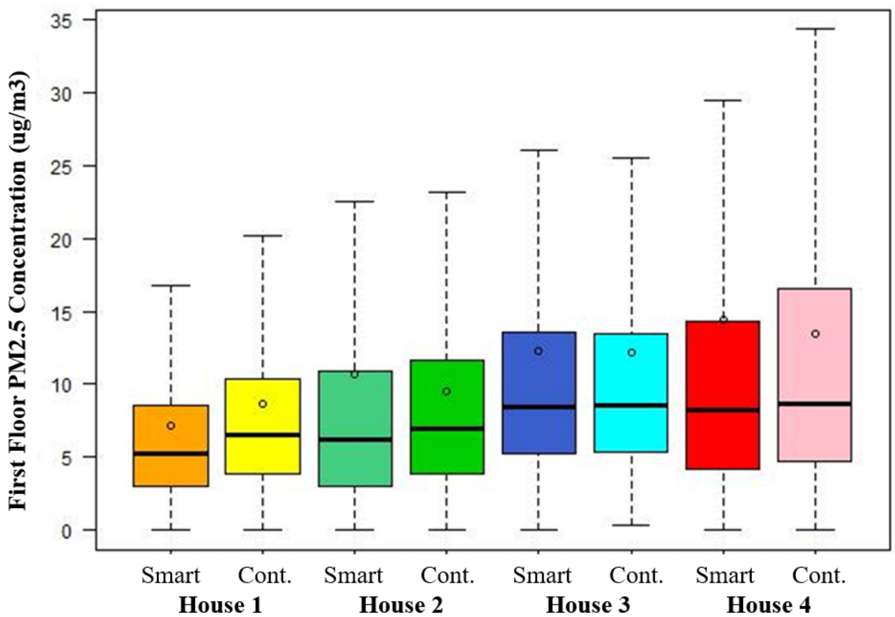

Figure 17. $PM_{2.5}$ concentrations by ERV mode on the first floor of each test home

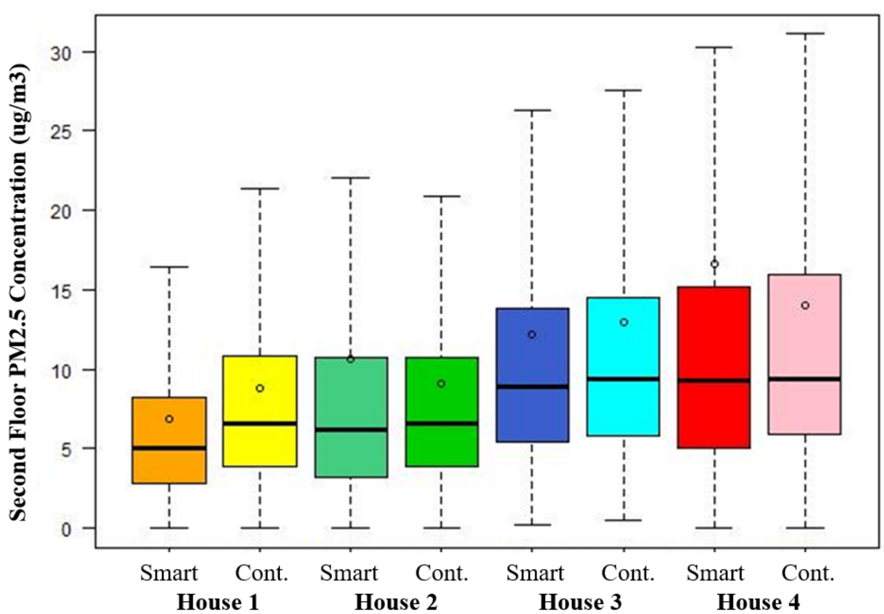

Figure 18. $PM_{2.5}$ concentrations by ERV mode on the second floor of each test home

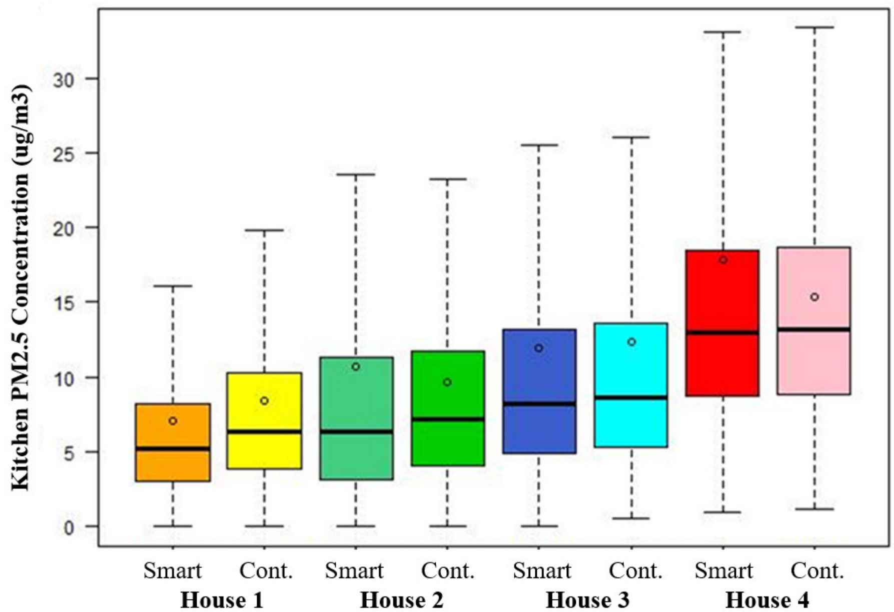

Figure 19. $PM_{2.5}$ concentrations by ERV mode in the kitchen (on the first floor) of each test home

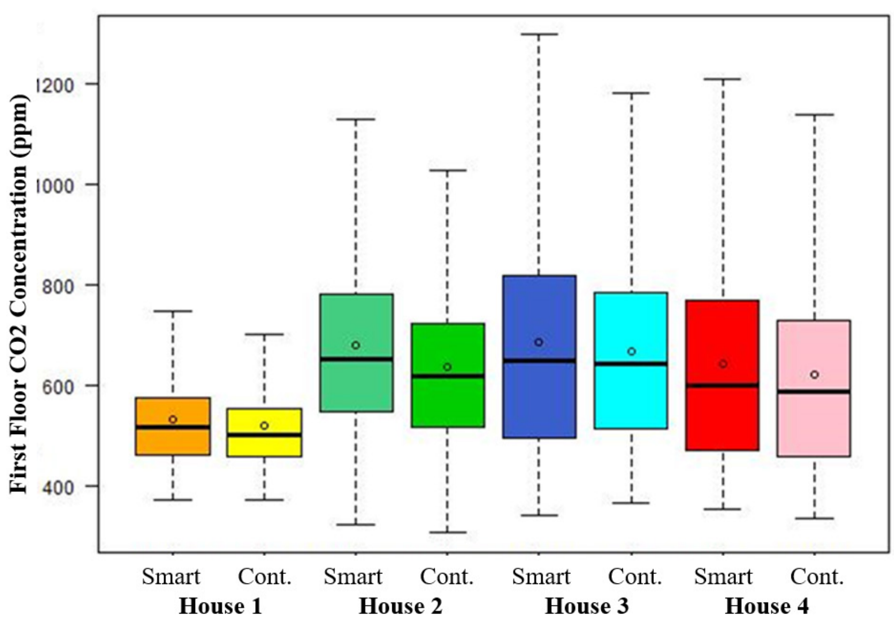

Figure 20. CO_2 concentrations by ERV mode on the first floor of each test home

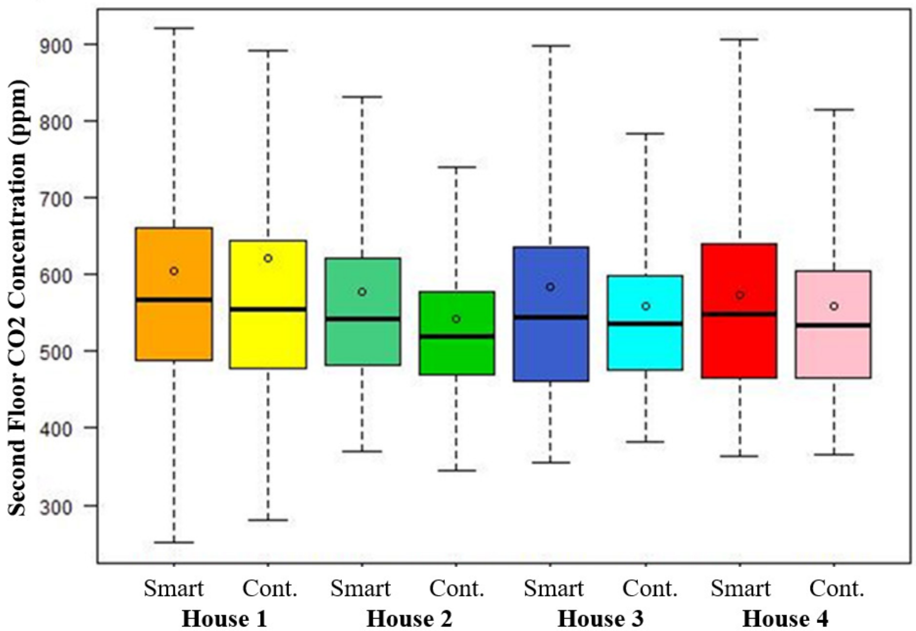

Figure 21. CO_2 concentrations by ERV mode on the second of each test home

Table 24 and Table 25 show the tabulated mean $PM_{2.5}$ and CO_2 concentrations in each ERV mode by house and microenvironment, as well as the t-test results. For each house, the location of the microenvironment monitored is listed in this order: outdoor, first floor location, second floor location, kitchen.

Table 24. $PM_{2.5}$ Concentrations by ERV Mode and T-Test Results

House	Microenvironment	Smart Mode		Continuous Mode		P-Value From T-Test
		Mean	Std. Dev.	Mean	Std. Dev.	
House 1	Outdoor	8.19	6.95	9.89	7.35	<0.0001
	Living Room	7.18	9.47	8.61	10.86	<0.0001
	M. Bedroom	6.85	8.00	8.78	9.69	<0.0001
	Kitchen	7.02	9.10	8.44	10.56	<0.0001
House 2	Outdoor	10.89	35.34	8.95	20.29	0.0016
	M. Bedroom	10.72	22.04	9.54	12.46	0.0020
	Living Room	10.60	22.15	9.09	10.87	<0.0001
	Kitchen	10.64	20.31	9.70	12.09	0.0078
House 3	Outdoor	8.60	19.34	8.72	15.31	0.7403
	M. Bedroom	12.27	14.78	12.20	16.63	0.8328
	Living Room	12.15	14.58	12.98	18.16	0.0180
	Kitchen	11.91	15.44	12.39	17.93	0.1774
House 4	Outdoor	8.10	7.39	8.43	6.95	0.0680
	M. Bedroom	14.45	20.90	13.45	17.18	0.0284
	Living Room	16.61	26.51	14.05	20.72	<0.0001
	Kitchen	17.80	21.21	15.38	12.17	<0.0001

Table 25. CO_2 Concentrations by ERV Mode and T-Test Results

House	Microenvironment	Smart Mode		Continuous Mode		P-Value From T-Test
		Mean	Std. Dev.	Mean	Std. Dev.	
House 1	Outdoor	439.76	28.38	443.43	26.97	<0.0001
	Living Room	534.40	112.99	519.87	101.94	<0.0001
	M. Bedroom	603.97	190.70	622.57	311.10	0.0019
House 2	Outdoor	451.05	34.91	451.87	34.62	0.2734
	M. Bedroom	681.73	182.87	636.63	163.47	<0.0001
	Living Room	577.19	146.69	541.93	123.16	<0.0001
House 3	Outdoor	455.77	38.38	458.19	37.58	0.0025
	M. Bedroom	687.41	234.71	667.06	189.58	<0.0001
	Living Room	583.47	175.09	558.19	129.07	<0.0001
House 4	Outdoor	456.10	32.12	457.93	33.59	0.0169
	M. Bedroom	642.35	204.04	623.34	192.27	<0.0001
	Living Room	573.04	144.70	558.20	144.77	<0.0001

Radon data were also analyzed to find average levels in each ERV mode (Table 26). However, due to the type of construction of the houses (concrete pier foundation with vented garages), the radon levels were extremely low on the first floor of the houses where the sensors were located. The resulting difference between ERV modes was inconsistent and minimal. House 1 had an additional radon sensor in it, the Airthings Corentium Pro, for reference.

Table 26. Test Home Annual Average Radon Levels in Each ERV Mode (pCi/L)

	Continuous Mode	Smart Mode
House 1 (Pro)	0.30	0.28
House 1	0.11	0.11
House 2	0.09	0.12
House 3	0.13	0.15
House 4	0.08	0.09

3.3.2 IAQ Regression Model Results

Linear mixed effect models were used to further test whether the differences in IAQ were statistically significant when controlling for sampling date, household variances, and other factors. The results are summarized in this section, with detailed model outputs available in Appendix B. For $PM_{2.5}$, the regression consisted of a linear mixed effect model with random intercepts for each field sampling date, with control for autoregressive correlation between each sampling date.

When adjusting for covariates including outdoor $PM_{2.5}$ concentrations, microenvironment (e.g., first floor, second floor, kitchen), indoor temperature and humidity, as well as household as fixed effect (e.g., House 1, 2, 3, or 4), indoor $PM_{2.5}$ concentration was 0.77 ug/m^3 lower ($p=0.049$) when using smart mode, compared to the sampling period using continuous mode. Sensitivity analysis was conducted where household was adjusted as a random effect (i.e., random intercept) in the regression models. Similar results were observed: indoor $PM_{2.5}$ concentration was 0.84 ug/m^3 lower ($p=0.043$) when using smart mode, compared to the sampling period using continuous mode. A similar trend was also observed when examining the impact of ERV modes on indoor levels of PM_1 and PM_{10}, where smart mode lowered the indoor PM_1 and PM_{10} by 0.55 ug/m^3 ($p<0.05$) and 0.31 ug/m^3, respectively.

Unfortunately, potentially due to the impact of extreme values and complexity of the random effect structure, the regression model failed to converge when examining whether the differences in CO_2 levels were statistically significant between the two ERV modes.

Table 27. Summary of Regression Model Results

	Household Modeled as Fixed Effect		Household Modeled as Random Effect	
IAQ Metric	Smart Mode Difference	Significance	Smart Mode Difference	Significance
PM_1	0.55 ug/m³ lower	p=0.033	0.61 ug/m³ lower	p=0.020
$PM_{2.5}$	0.77 ug/m³ lower	p=0.049	0.84 ug/m³ lower	p=0.043
PM_{10}	0.31 ug/m3 lower	p=0.493	0.33 ug/m3 lower	p=0.468
CO_2	N/A	N/A	N/A	N/A

3.3.3 In-Situ Gravimetric $PM_{2.5}$ Monitor Comparison Results

Gravimetric $PM_{2.5}$ sampling was conducted using Harvard Personal Exposure Monitors with 37-mm Teflon filters in House 1 and 2, alongside the low-cost PM sensors. Each measurement sample lasted 24 hours. Overall, a total of eight 24-hour samples were collected. The low-cost $PM_{2.5}$ data are the average between two co-located sensors. The analysis was also performed using only one of the two co-located sensors yielding very similar results, so only the average is presented below.

Across these eight observations, the low-cost sensors performed fairly well, having a 0.88 correlation coefficient with the Harvard Personal Exposure Monitors measurements, and an average 0.67 ug/m^3 difference in $PM_{2.5}$ levels. The absolute precision of the low-cost sensors was 1.46 ug/m^3, and the relative precision was 18.4%.

Table 28. Summary of Gravimetric $PM_{2.5}$ Daily Average Comparison Results

	Date	Harvard Personal Exposure Monitors Daily Average (ug/m³)	Low-Cost $PM_{2.5}$ Sensor Daily Average (ug/m³)	Difference (ug/m³)
House 1	6/13/2019	4.9	7.5	2.7
	6/14/2019	5.2	7.7	2.5
House 2	6/13/2019	5.9	8.3	2.4
	6/14/2019	8.0	8.9	0.9
	9/12/2019	6.4	6.0	-0.5
	9/13/2019	14.0	11.0	-3.0
	9/12/2019	4.4	6.2	1.8
	9/13/2019	11.9	10.5	-1.4
Average		**7.60**	**8.28**	**0.67**
Absolute Precision		**1.46 ug/m³**		
Relative Precision		**18.4%**		

3.3.4 Low-Cost IAQ Sensor Chamber Testing Results

For the sake of brevity and adhering specifically to the research questions in the body of this report, detailed tables and analysis of chamber testing results are located in Appendix C.

In summary, the CV and RPD values indicate acceptable performance of the temperature sensors and RH sensors individually and as a group, acceptable performance of the CO_2 sensors individually and as a group after background calibration is performed, and qualified acceptable performance of the PM sensors individually and as a group.

3.3.5 IAQ Results Summary

Research Question 2: Using low-cost IAQ sensors whose performance has been independently verified, is there a discernable difference between measured indoor air pollutants when comparing continuous and smart ERV operation modes?

Conclusion: We found measurable, albeit small differences in both CO_2 and PM concentrations when comparing smart and continuous ERV modes. We directly compared PM levels between modes using mixed effect regression modeling, which showed that PM_1 and $PM_{2.5}$ concentrations were lower in smart mode to a statistically significant degree. Although we could not compare the CO_2 levels using the same approach, every microenvironment within every house was measured to have slightly higher median levels of CO_2 in smart mode compared to continuous mode. The mean CO_2 levels were also higher in smart mode to a statistically significant degree, per t-test results, for every house and microenvironment except for House 1's master bedroom. The average radon levels were extremely low in all houses due to the type of foundation construction used, so differences were negligible between ERV modes. It should be emphasized that although we did measure differences by mode for the pollutants, which for some were statistically significant, differences in the physical concentrations were small. Based on these findings, we believe that caution should be taken when making inferences regarding the role of ERV mode in either reducing or enhancing indoor pollutant levels.

3.4 Energy Analysis Results

3.4.1 HVAC Energy Analysis and BEopt Comparison Results

Energy models were constructed in BEopt for all four houses to compare the five ventilation options described in Section 2.1.6. These five options are:

1. A Broan ERVS100S in time-varying (smart) mode at the field-measured supply flow rate for each house (93.7 cfm average, but varies by house; see Table 7.)
2. A Broan ERVS100S in continuous mode at the field-measured supply flow rate for each house (93.7 cfm average, but varies by house; see Table 7.)
3. A Broan ERVS100S equivalent in continuous mode, exactly sized at the ASHRAE 62.2-2016 Q_{fan} requirement for each house (54.0 cfm average, but varies by house; see Table 7.)

4. A CFIS system (the builder's standard ventilation method) at the ASHRAE 62.2-2016 Q_{tot} requirement for each house (106.6 cfm average, but varies by house; see Table 7.)
5. A CFIS system at the ASHRAE 62.2-2016 Q_{fan} requirement for each house (54.0 cfm average, but varies by house; see Table 7.)

As seen in Figure 22, the whole-house energy models for smart and continuous mode tended to be lower than the weather-normalized billed and metered data for each home. As a note, the billed and metered totals are composed of half smart mode and half continuous mode ERV operation. Also, because of a malfunction of the electricity monitoring equipment, House 2 site-monitored usage data were not collected. The difference between billed and metered data is likely due to billing dates not aligning directly with the first day of every month, so also misaligning with the heating degree days and cooling degree days quantities used in the weather normalization. The more exact metered data is used for direct A/C condensing unit and ERV energy usage below.

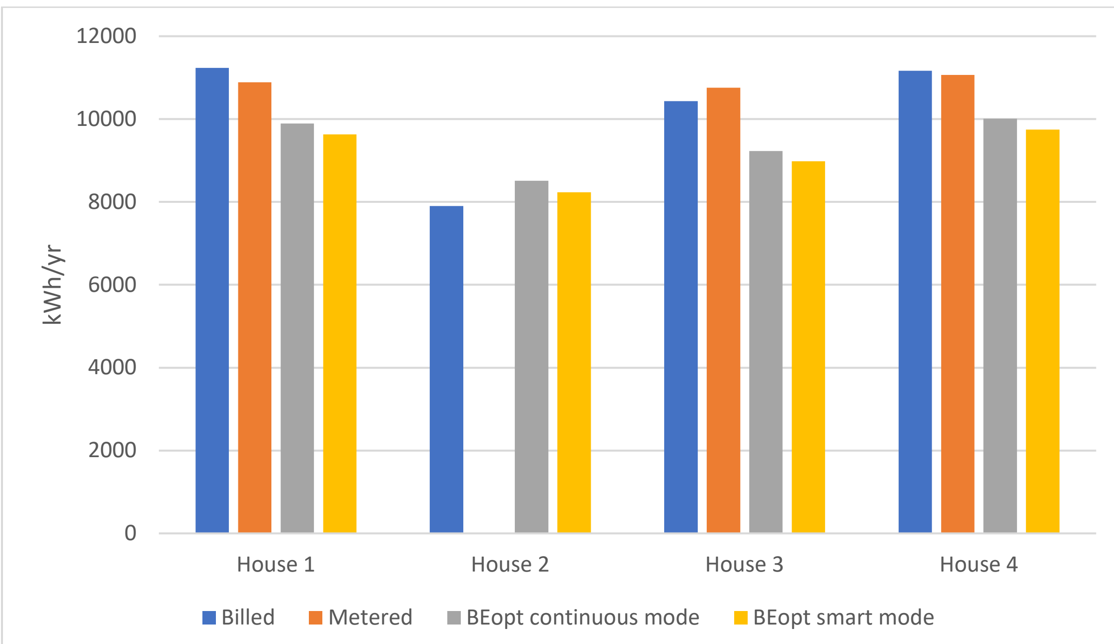

Figure 22. Weather-normalized whole-house annual kWh consumption, billed vs. metered vs. modeled

Figure 23 shows how the weather-normalized natural gas billed consumption compared to the modeled results. The larger discrepancy for House 2 and House 4 is likely because both houses had gas lanterns on their front porch, which were unaccounted for in the models.

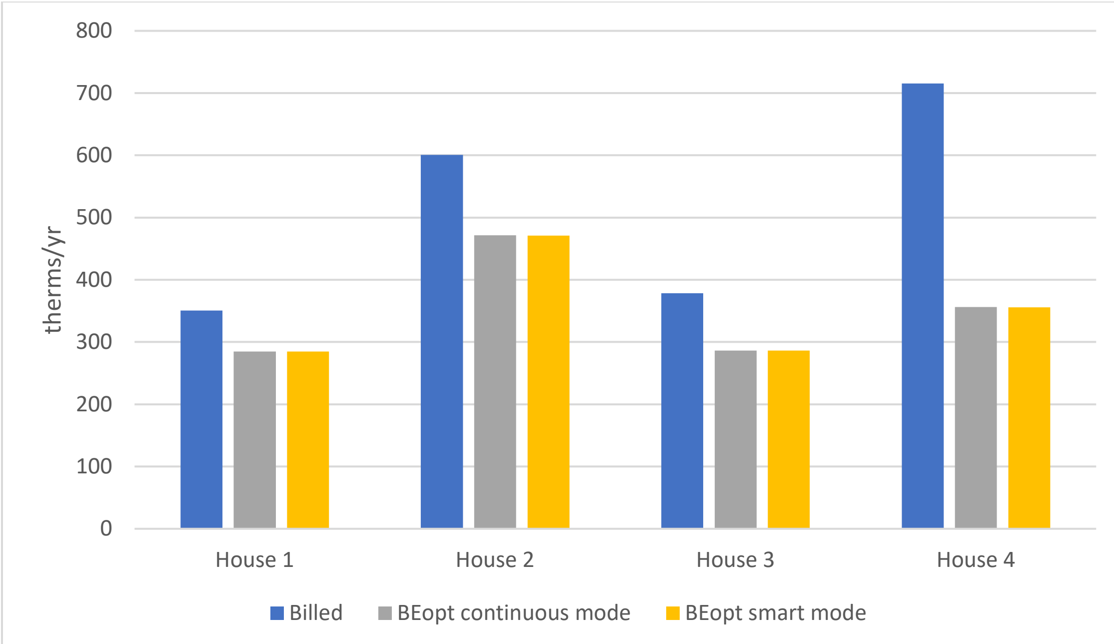

Figure 23. Weather-normalized test home annual therm consumption, billed vs. modeled

The simulated whole-house and end-use energy results from BEopt for the five ventilation options can be seen in Figure 24, and the therm results can be seen in Figure 25. The tabulated results can be seen in Table 29 and Table 30, compared to the B10 benchmark[20] for reference. As noted in Section 2.3: Analysis Methods, the raw output from BEopt for the ERV models contained errors, so the values presented here are corrected using calculations external to BEopt. More detail on these corrections and our guess as to the underlying bug is presented in Appendix D.

In every case, as expected, the houses with the smart ERV used less electricity than that same ERV running continuously, ranging from 2.6%–3.3% savings. However, houses with a continuously running ERV sized exactly at Q_{fan} for each house used less electricity than even the smart ERV (3.4%–4.7% savings over smart). The savings occurred in three end uses: cooling (A/C), cooling fan (AHU blower during cooling season), and vent fan (ERV energy usage). The two CFIS options used similar amounts of electricity and used more than any of the ERV options in every house (0.2%–3.8% more than the baseline continuous ERV).

The gas usage was very similar between the homes with smart and continuous ERV modes, with minimal heating savings (0.09%–0.11%). The Q_{fan} ERV had 0.9%–2.3% savings compared to the smart option. The CFIS at Q_{tot} option used more gas than any other configuration in all houses (4.9%–12.0% more than the baseline continuous ERV). The CFIS at Q_{fan} used 0.2%–

[20] NREL developed the concept of a new construction reference building that represents the typical code-built house according to 2009 International Energy Conservation Code (IECC 2009). To view the *2014 Building America House Simulation Protocols,* see Hendron and Engebrecht (2010): https://www.energy.gov/sites/prod/files/2014/03/f13/house_simulation_protocols_2014.pdf.

3.8% less gas than the baseline continuous ERV option. All differences between options were within the heating end use.

It is worth noting that relative exposure for smart mode at the tested flow rates was about 18% lower than unity on average (Table 35), and that smart systems optimized for relative exposures of unity for each house would have lower flow rates and less energy usage.

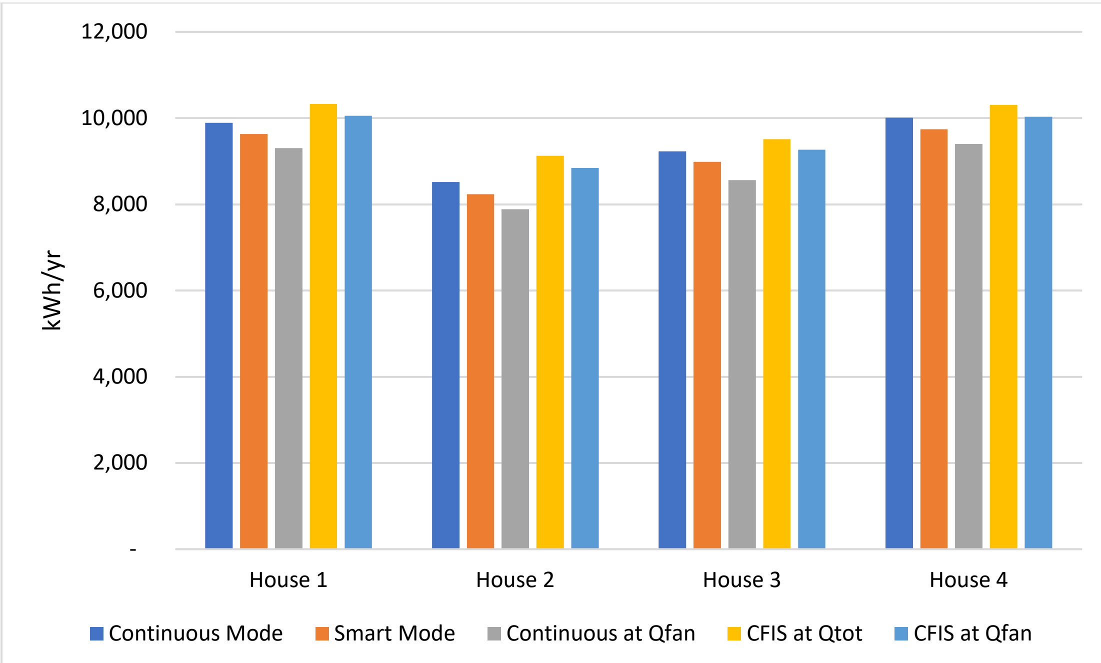

Figure 24. BEopt model annual kWh usage results for the five ventilation options

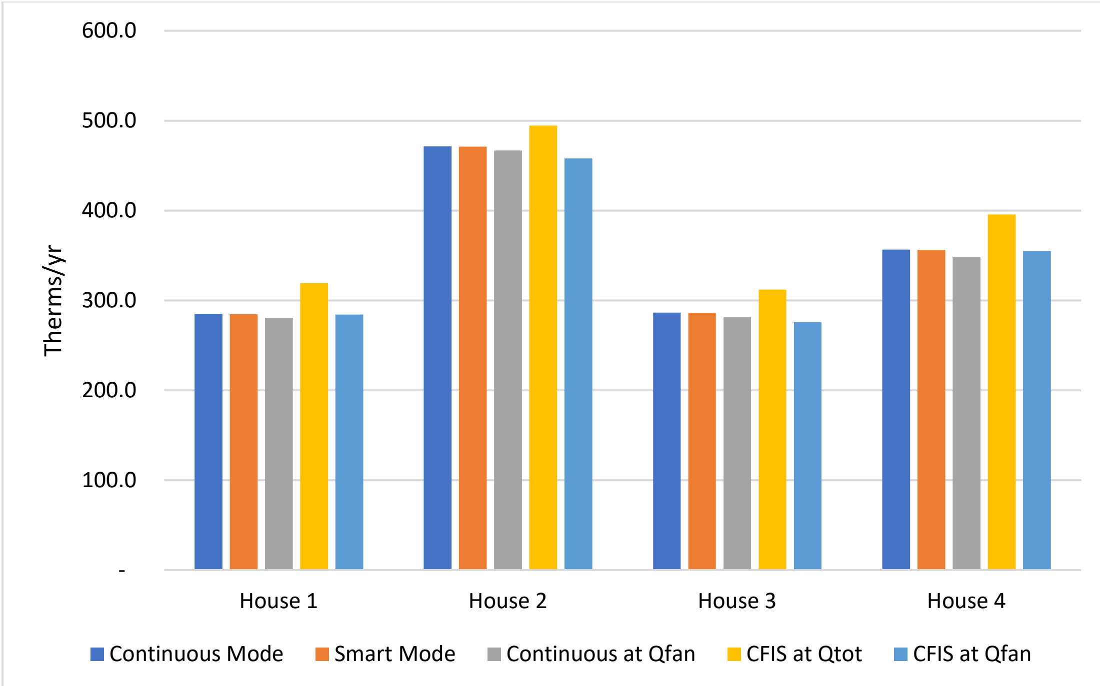

Figure 25. BEopt model annual therm usage results for the five ventilation options

Table 29. BEopt Model Annual kWh Usage Results by End Use for the Five Ventilation Options

	End Use	B10 Benchmark	Continuous ERV	Smart ERV	Continuous ERV at Q_{fan}	CFIS at Q_{tot}	CFIS at Q_{fan}
House 1	Misc.	2,664.1	2,664.1	2,664.1	2,664.1	2,664.1	2,664.1
	Vent Fan	105.5	903.9	795.8	387.9	849.9	861.7
	Large Appliances	2,394.5	2,045.7	2,045.7	2,045.7	2,045.7	2,045.7
	Lights	1,972.5	1,263.2	1,263.2	1,263.2	1,263.2	1,263.2
	Cooling Fan/Pump	621.3	562.7	533.8	559.8	636.0	586.2
	Heating Fan/Pump	228.6	49.8	47.3	49.8	61.6	49.8
	Cooling	2,558.6	2,376.9	2,254.7	2,306.6	2,784.3	2,558.6
	Hot Water	-	26.4	26.4	26.4	26.4	26.4
	Total	**10,545**	**9,893**	**9,631**	**9,303**	**10,331**	**10,056**
House 2	Misc.	2,464.8	2,464.8	2,464.8	2,464.8	2,464.8	2,464.8
	Vent Fan	90.9	903.9	795.8	346.7	1,084.4	1,084.4
	Large Appliances	2,116.1	680.0	680.0	680.0	680.0	680.0
	Lights	1,931.4	1,066.8	1,066.8	1,066.8	1,066.8	1,066.8
	Cooling Fan/Pump	512.9	767.9	728.4	750.3	882.2	806.0
	Heating Fan/Pump	381.0	108.4	102.9	105.5	114.3	102.6
	Cooling	1,943.1	2,500.0	2,371.5	2,450.2	2,807.7	2,614.3
	Hot Water	-	23.5	23.5	23.5	23.5	23.5
	Total	**9,440**	**8,515**	**8,234**	**7,888**	**9,124**	**8,842**

	End Use	B10 Benchmark	Continuous ERV	Smart ERV	Continuous ERV at Q_{fan}	CFIS at Q_{tot}	CFIS at Q_{fan}
House 3	Misc.	2,623.1	2,623.1	2,623.1	2,623.1	2,623.1	2,623.1
	Vent Fan	105.5	903.9	795.8	314.3	864.6	861.7
	Large Appliances	2,394.5	1,975.4	1,975.4	1,975.4	1,975.4	1,975.4
	Lights	1,890.4	1,043.4	1,043.4	1,043.4	1,043.4	1,043.4
	Cooling Fan/Pump	609.6	468.9	444.8	451.4	542.2	483.6
	Heating Fan/Pump	216.9	52.8	50.0	52.8	61.6	49.8
	Cooling	2,511.7	2,133.7	2,024.0	2,075.0	2,376.9	2,204.0
	Hot Water	-	26.4	26.4	26.4	26.4	26.4
	Total	**10,352**	**9,227**	**8,983**	**8,562**	**9,513**	**9,267**
House 4	Misc.	2,634.8	2,634.8	2,634.8	2,634.8	2,634.8	2,634.8
	Vent Fan	105.5	903.9	795.8	401.9	767.9	767.9
	Large Appliances	2,394.5	1,864.0	1,864.0	1,864.0	1,864.0	1,864.0
	Lights	1,913.8	1,544.6	1,544.6	1,544.6	1,544.6	1,544.6
	Cooling Fan/Pump	618.4	527.6	500.4	524.6	603.8	551.0
	Heating Fan/Pump	225.7	76.2	72.3	73.3	90.9	76.2
	Cooling	2,541.0	2,432.6	2,307.6	2,330.0	2,775.5	2,567.4
	Hot Water	-	26.4	26.4	26.4	26.4	26.4
	Total	**10,434**	**10,010**	**9,746**	**9,400**	**10,308**	**10,032**

Table 30. BEopt Model Annual Therm Usage Results by End Use for the Five Ventilation Options

	End Use	B10 Benchmark	Continuous ERV	Smart ERV	Continuous ERV at Q_{fan}	CFIS at Q_{tot}	CFIS at Q_{fan}
House 1	Heating	316.0	151.8	151.5	147.8	185.9	151.3
	Hot Water	170.3	115.3	115.3	115.3	115.3	115.3
	Large Appliances	0.0	17.8	17.8	17.8	17.8	17.8
	Total	**486.3**	**284.9**	**284.6**	**280.9**	**319.0**	**284.4**
House 2	Heating	512.4	318.0	317.5	313.3	341.1	304.4
	Hot Water	161.5	95.2	95.2	95.2	95.2	95.2
	Large Appliances	0.0	58.3	58.3	58.3	58.3	58.3
	Total	**673.9**	**471.5**	**471.0**	**466.8**	**494.6**	**457.9**
House 3	Heating	302.6	163.3	163.0	158.3	188.9	152.4
	Hot Water	176.8	105.4	105.4	105.4	105.4	105.4
	Large Appliances	0.0	17.8	17.8	17.8	17.8	17.8
	Total	**479.4**	**286.5**	**286.2**	**281.5**	**312.1**	**275.6**
House 4	Heating	312.8	227.9	227.5	219.5	267.0	226.6
	Hot Water	176.8	110.7	110.7	110.7	110.7	110.7
	Large Appliances	0.0	17.8	17.8	17.8	17.8	17.8
	Total	**489.6**	**356.4**	**356.0**	**348.0**	**395.5**	**355.1**

The modeled ERV fan energy usage was compared directly with the metered ERV energy usage by extrapolating the metered ERV fan energy usage in each mode to a whole year. The extrapolation assumed that the percentage of time in standby, as monitored during smart mode periods, was representative of the entire year. The actual average wattage for each ERV was used for the calculations. On average, both the raw kWh savings and % savings were accurate (3.3% difference and 0.4% difference, respectively), with the largest discrepancy being House 1. However, as detailed in Section 3.4.2, because of the staggering of monitoring periods, House 1 experienced a different summer, and thus different outdoor T/RH conditions than the other houses.

Table 31. Test Home Annual ERV Fan Energy Usage (kWh) in Smart vs. Continuous Mode

	Continuous Mode	Smart Mode	kWh/yr Savings	% Savings
House 1	883.5	797.5	86.0	9.7%
House 2	875.3	750.2	125.1	14.3%
House 3	881.2	771.6	109.6	12.4%
House 4	884.0	786.8	97.2	11.0%
House 1–4 Average	**881.0**	**776.5**	**104.5**	**11.9%**
BEopt TMY	**880.4**	**772.3**	**108.1**	**12.3%**

In order to make a direct comparison between metered annual A/C usage in smart mode and in continuous mode, A/C condensing unit energy usage was regressed against actual heating degree days and cooling degree days data as well as ERV mode. The regression was then used to extrapolate full-year weather-normalized energy usage for each house in each mode. The models were all highly accurate, with R^2 values of 0.96 each. The results can be seen in Table 32, compared to the modeled results in BEopt. Although the A/C savings predictions of the BEopt models were not very accurate in terms of raw kWh savings, they were reasonably accurate in terms A/C savings percentage (5.2% savings predicted vs. 7.5% actual on average).

Table 32. Test Home Annual A/C Condenser Energy Usage (kWh/yr) in Smart vs. Continuous Mode

	BEopt Model A/C kWh/yr				Daily Total Metered A/C kWh/yr (regressed and weather-normalized, R^2=0.96 for each house)			
	Continuous Mode	**Smart Mode**	**kWh/yr savings**	**% Savings**	**Continuous Mode**	**Smart Mode**	**kWh/yr savings**	**% Savings**
House 1	2,738.3	2,595.3	143.0	5.2%	4,338.8	4,056.5	282.3	6.5%
House 3	2,340.2	2,221.6	118.6	5.1%	3,451.5	3,173.0	278.5	8.1%
House 4	2,738.3	2,595.3	143.0	5.2%	3,608.6	3,307.3	301.3	8.3%
Average	**2,605.6**	**2,470.7**	**134.9**	**5.2%**	**3,799.6**	**3,512.3**	**287.4**	**7.6%**

3.4.2 ERV Performance Analysis

The percentage of time each ERV was in standby is compared to the expected performance in Table 33. The expected percentage is based on TMY weather data exported from BEopt. All ERVs were within ±3% of the expected TMY performance. It appears that the variations are due mostly to variations in weather from TMY data and from the fact that the house monitoring periods were staggered so House 1 experienced a different summer from the rest, and Houses 1 and 3 experienced a different fall than Houses 2 and 4. These trends are reflected in the data in Table 34. As expected, there was 0% standby time when the ERVs were in continuous mode, so those data are excluded from the seasonal representation in Table 34. Also included is the equivalent average annual cfm in continuous and smart mode in each house.

Table 33. Test Home Annual ERV % Time in Standby and Average Supply cfm

	Continuous Mode		Smart Mode	
	% Time in Standby	Average cfm	% Time in Standby	Average cfm
Modeled TMY	0%	*	12.9%	-
House 1	0%	93.0	9.9%	83.8
House 2	0%	84.5	14.7%	72.1
House 3	0%	99.9	12.9%	87.0
House 4	0%	97.7	11.5%	86.4

**The modeled ERVs used the measured average cfm of each house. So, the "Modeled TMY" % time in standby is the same for all houses, but the average modeled cfm in continuous and smart modes are different for each house.*

Table 34. Test Home Seasonal ERV % Time in Standby and Average cfm When in Smart Mode

	Spring		Summer		Fall		Winter	
	% Time in Standby	Average cfm	% Time in Standby	Average cfm	% Time in Standby	Average cfm	% Time in Standby	Average cfm
Modeled TMY	18.4%	*	20.5%	-	11.3%	-	0.6%	-
House 1	18.4%	75.9	8.0%	85.5	11.3%	82.5	2.3%	90.8
House 2	24.4%	63.9	21.3%	66.5	9.3%	76.6	3.8%	81.3
House 3	22.2%	77.7	16.1%	83.8	11.0%	88.9	2.5%	97.4
House 4	21.9%	76.3	11.4%	86.5	9.3%	88.6	3.5%	94.2

**The modeled ERVs used the measured average cfm of each house. So, the "Modeled TMY" % time in standby is the same for all houses, but the average modeled cfm in continuous and smart modes are different for each house.*

The resulting relative exposure calculation for each house can be seen in Table 35. Actual relative exposure was calculated assuming field-monitored smart mode behavior (time periods and durations when the ERVs are in standby) could be accurately extrapolated to the periods when the ERVs were actually in continuous mode. The following relative exposure calculations also factor in the field-tested blower door results (Table 6). All relative exposure values were below 1, even when factoring in EATR, meaning in every case the homes complied with ASHRAE 62.2-2016.

Table 35. Test Home Annual Average Relative Exposure (Annual Average Peak Relative Exposure in Parenthesis) per ASHRAE 62.2-2016 Appendix C

	Expected TMY Relative Exposure at Field-Tested ERV Supply cfm	Actual Relative Exposure at Field-Tested ERV Supply cfm	Actual Relative Exposure at Field-Tested ERV Supply cfm, Factoring in EATR
House 1	0.86 (1.67)	0.84 (2.00)	0.86 (2.00)
House 2	0.86 (1.56)	0.87 (1.87)	0.89 (1.87)
House 3	0.75 (1.43)	0.75 (1.41)	0.77 (1.43)
House 4	0.85 (1.73)	0.83 (2.19)	0.85 (2.19)

The annual average ERV-induced sensible and latent loads—as well as the average induced water vapor load—in both smart and continuous modes are shown in Table 36. As specified in Section 2.3.3.2.2, "Actual" induced load takes into account the fact that, as installed, some of the ERVs were unbalanced, putting the house under negative pressure and creating a net flow of outside air into the space. The "Ideal" case shows what the induced loads would be if the ERVs were perfectly balanced at the supply airflow rate, not factoring in a net flow of outside air.

Table 36. Test Home Annual ERV-Induced Loads (Actual vs. Ideal)

		Actual (Includes Net OA)		Ideal (Balanced, No Net OA)	
Metric	**House**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**
Average Induced Water Vapor Flow rate (lbs/hr)	House 1	0.99	0.81	0.64	0.52
	House 2	0.61	0.52	0.38	0.33
	House 3	0.50	0.35	0.50	0.35
	House 4	0.56	0.53	0.47	0.45
Average Induced Latent Load (Btu/hr)	House 1	1,038.73	855.1	670.2	546.4
	House 2	644.1	550.5	397.8	344.5
	House 3	530.4	364.4	530.4	364.4
	House 4	590.1	560.7	496.2	469.9
Average Induced Sensible Load (Btu/hr)	House 1	157.7	118.8	135.0	104.7
	House 2	42.2	27.9	55.3	108.3
	House 3	18.1	-15.9	18.1	-15.9
	House 4[21]	-118.9	-77.7	-41.2	-21.1

Additional in-situ ERV performance metrics such as induced loads by season, ERV effectiveness, and ERV effectiveness by season are presented in Appendix E.

Research Question 3: How much space-conditioning energy is saved and how accurately can BEopt models (with customized time-varying ventilation scripts) predict HVAC energy savings for test homes switching between smart and continuous operation modes?

Conclusion: We were able to compare the test home and the model energy consumption for the A/C end use and the ERV itself, but not for the furnace. The A/C savings prediction was not very accurate in terms of raw kWh savings, but was reasonably accurate in terms of A/C savings percentage (5.2% savings predicted vs. 7.6% actual, on average). The ERV savings prediction was accurate both with regards to kWh and kWh percentage savings.

The BEopt house models, which compared various ventilation options, showed 2.6%–3.3% overall electricity savings and very marginal gas savings for smart mode compared to continuous mode. The CFIS at Q_{tot} models used 3.0%–7.1% more electricity and 4.9%–12.0% more gas than the baseline continuous ERV model. The CFIS at Q_{fan} models used 0.2%–3.8% more electricity and 0.2%–3.8% less gas than the baseline continuous ERV model. The overall lowest electricity and gas use was for a continuous ERV sized at the exact Q_{fan} requirement per ASHRAE 62.2-2016 (3.4%–4.7% kWh savings and 0.9%–2.3% gas savings over smart mode).

The actual relative exposure for each house was similar to the prediction based on BEopt simulation data. ERV field performance was also calculated, showing in-situ performance consistent with lab tests.

[21] House 4 is negative annually because when averaging all seasons, some seasons have positive net ERV loads and some negative. This varied by house based on actual months tested, ERV setup, and other factors.

3.5 Other Results and Observations

Upon uninstallation of the monitoring equipment and T/RH probes from the ERV at the conclusion of the 12-month monitoring period, we observed a buildup of some material on the probe in the supply air inlet duct of every house (position X_1 in Figure 12). However, there was no sign of any buildup on the probes or ducts of any of the other ERV arms. Photos of each probe at position X_1 can be seen in Figure 26, and a photo of the inside of duct X_1 can be seen in Figure 27. Photos of all the probes with no signs of buildup at position X_2 can be seen in Figure 28.

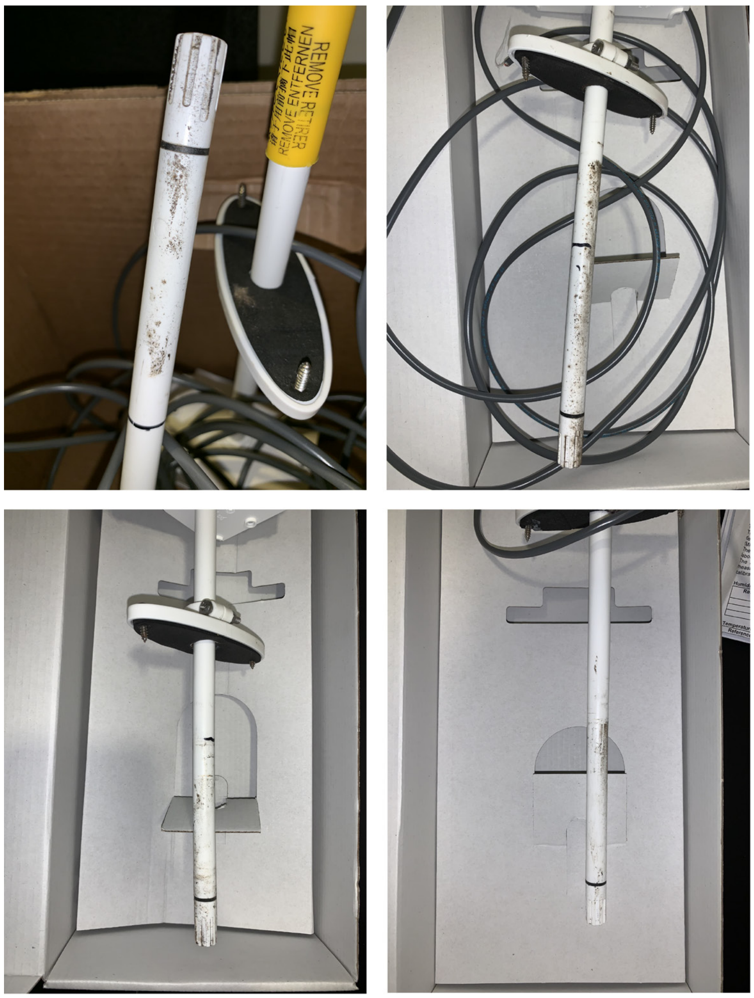

Figure 26. Photos of each of the X_1 duct probes from test homes 1–4 (clockwise, from top left)

Figure 27. Photo of inside of X_1 duct from test home 3 (representative of the X_1 duct in other homes)

The Southface team had the X_1 position probes examined by Dr. Ginger Chew at the Centers for Disease Control and Prevention in Atlanta, Georgia. Dr. Chew confirmed that the buildup on each of the probes was, indeed, mold. She found “a variety of spore types, but predominantly Cladosporium (a common outdoor and indoor mold genus).”

As mentioned, there was no sign of any mold on the probes or the ducts downstream of the ERV (Figure 28). We suspect that the ERV filters (MERV 7 in all of the units) and the tempering of the air by the ERV prevented any mold growth in the X_2 ducts. Thus, all mold presence was separated from the occupant living area by the ERV.

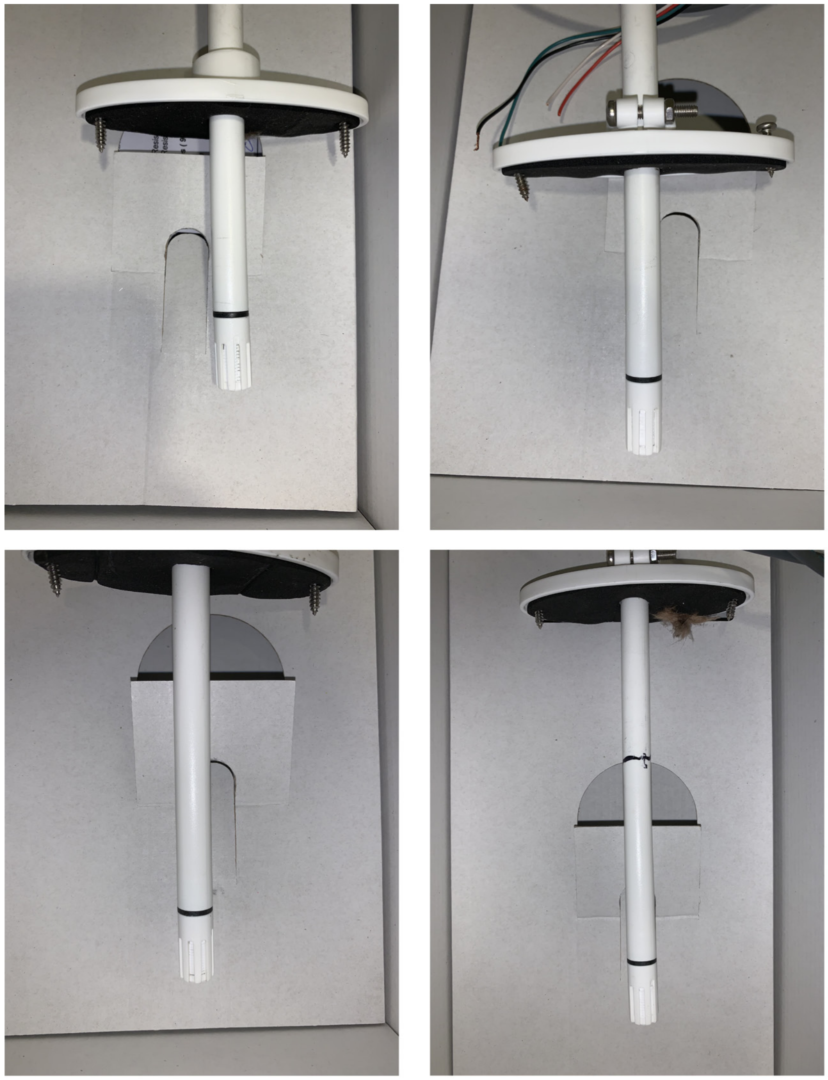

Figure 28. Photos of each of the X_2 duct probes from test homes 1–4 (clockwise, from top left)

To try to understand the cause of the mold growth, the Southface team examined the duct T/RH data as well as the outdoor sensor and local weather station data (Table 37). The data from the outdoor T/RH sensors make it appear that the air is cooling within the ducts; however, there is no probable mechanism for this cooling when comparing duct temperature data to attic temperature data, but rather probable mechanisms for *heating* of the ducts within the vented attic during sunny days. Additionally, the local weather station data matches the ERV X_1 data so closely that it is likely the outdoor T/RH sensor under the covered back porch is providing misleading readings because it is experiencing a proximity effect where the sensed temperatures at night are higher, and thus the RH values are lower. The fresh air intakes for each house run either through the attic wall or through the soffit, and so they are 30–40 ft above ground level. This is evidently sufficient to create a significant difference in measured T/RH compared to the outdoor sensor location under the back porch.

Both the weather station and ERV X_1 data agree that the RH exceeded 80% about 50% of the time. It also exceeded 90% RH about 30% of the time, 95% RH about 12% of the time, and 99% RH about 2% of the time. With only 2% of time above 99%RH (condensing conditions), it is surprising that there would be so much mold growth according to the conventional wisdom that condensation is necessary for growth. However, this finding is similar to Less et al. (2019), who found mold growth in a sealed attic despite a lack of condensing conditions.

For a drastic comparison of the duct conditions after fresh air passes through the ERV core, the results for X_2 are shown to the right of the X_1 results in the following table. The ERV does an excellent job of protecting the X_2 duct, as well as the house, from high humidity.

Table 37. Annual Percentage of Time Above Various RH Thresholds

Threshold	Outdoor T/RH Sensor for House 3	Local Weather Station	ERV X_1 In-Duct T/RH Probe	ERV X_2 In-Duct T/RH Probe
% time above 80% RH	34.4%	54.0%	48.8%	0.16%
% time above 90% RH	4.6%	29.6%	27.3%	0.09%
% time above 95% RH	0.3%	11.3%	13.5%	0.07%
% time above 99% RH	0.003%	2.1%	2.1%	0.05%

4 Discussion

As discussed in Section 3: Results, the smart ventilation algorithm created a more comfortable indoor environment on an annual basis, but this effect was inconsistent during the spring, summer, and fall months, and only directionally consistent during the winter months. Our suspicion from the analysis is that this is primarily due to the long runtimes and associated dehumidification activity of the A/C units in response to the high sensible loads in Charleston. This highlights the importance of proper design and commissioning of A/C equipment in regions with high latent loads. Proper design and commissioning ensures that the sensible heat ratio of the system is correct for the climate, which allows for sufficient dehumidification to occur.

One outcome of this is that the smart ERV control strategy—designed and intended initially for hot-humid climates—might actually be more widely applicable to other climates such as mixed-humid and marine with high latent loads but not the higher sensible loads that drive A/C runtimes. We propose further field testing of this type of system in these other climates where the sensible load is lower relative to latent load, but A/C is still installed.

Because the difference in comfort metrics between smart and continuous modes was neither as consistent nor as distinct as expected, we suggest further testing of the smart ERV control strategy under more precise, controlled conditions. Specifically, a comparison between a smart ERV and a continuous ERV, both with relative exposures of unity, would help distinguish the effect of the smart control strategy from a simple lower average equivalent flow rate (Table 33 and Table 34). Additionally, we suggest further field testing comparing the smart ERV control strategy with other ventilation strategies such as those only modeled with BEopt in this project. These other ventilation strategies would be systems such as a supply-only systems (CFIS), supply-only in-line fans, smart supply-only in-line fans, and exhaust-only systems.

Another HVAC quality assurance need highlighted by this study is the necessity for ERVs to be properly commissioned through verification of flow rates and balancing of the airstreams. As seen in the results and Appendix E, negatively unbalanced ERVs in humid climates can draw in large amounts of unwanted moisture over the course of a year, but positively unbalanced ERVs have less of this side effect.

Further, if desiring to implement a smart ventilation strategy, this study shows the amount of foresight, design, and calculations necessary to achieve ASHRAE 62.2 compliance. House size, layout, blower door test results, TMY weather data, and simulated smart ventilation behavior in response to TMY weather data are all required ahead of time to be able to perform the relative exposure calculations. A simplified tool for completing these types of calculations is likely needed if contractors are expected to readily adopt this technology and adhere to ASHRAE standards. Alternatively, an even smarter system that can compute relative exposure internally—or a “connected” system that can determine expected weather conditions from the internet and can vary its flow—can minimize up-front design requirements.

An unexpected finding of the study was the mold growth in the supply air inlet ducts (X_1 in Figure 12) of the houses. As a result, we recommend that the outside air supply of all ventilation systems be filtered and suggest avoiding exhaust-only strategies[22] in humid environments such as Charleston. An additional filter for the outside air, located at the fresh air inlet itself, may be necessary to prevent mold spores from entering the duct and preventing growth. Also, it may help to limit the length of duct leading from the outside air inlet to the mechanical ventilation device, or eliminate the duct entirely by locating the mechanical ventilation outdoors (in a covered area or weatherizing the device). These are strategies similar to those used in dedicated outdoor air systems (DOAS) in the commercial sector.

We believe further research is needed to explore various strategies to prevent mold growth in similar climates in outside air ducts. We also recommend research examining mold growth in outside air ducts in different climates to see if this phenomenon is unique to Charleston. Anecdotally, we examined similarly installed systems in Atlanta and found no evidence of mold. We believe exploring this further and issuing guidance as to best mechanical ventilation practices in each climate zone is warranted.

[22] The implication here is that if mold is growing in a duct, we do not recommend exhaust-only strategies where the intake “duct” is the envelope, and mold growth cannot be easily monitored.

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Appendix A: Homeowner Comfort Surveys

<u>Pre- and Post-Monitoring Period (Annual) Online Survey</u>

The following survey questions, adapted from the *Healthy Efficient New Gas Homes (HENGH) Field Study Protocol* (Chan et al. 2016), were answered by each homeowner prior to the year-long monitoring period and again following the year-long monitoring period.

1. How many people live in your home?

2. To what extent are you satisfied or dissatisfied with the indoor air quality of your home?
   a. Very satisfied
   b. Satisfied
   c. Neutral
   d. Unsatisfied
   e. Very unsatisfied

3. How would you rate the outdoor air quality near where you live?
   a. Very satisfied
   b. Satisfied
   c. Neutral
   d. Unsatisfied
   e. Very unsatisfied

4. How would you rate your home in protecting you from outdoor air pollution?
   a. Very effective
   b. Satisfied
   c. Neutral
   d. Unsatisfied
   e. Very ineffective

5. In **<u>winter,</u>** how often is the temperature in your home uncomfortable to any occupants because some room(s) are too hot or too cold?

	Never	Few times a year	Few times a month	Few times a week	Every day
Too hot in some room(s)					
Too cold in some room(s)					

6. In **summer,** how often is the temperature in your home uncomfortable to any occupants because some room(s) are too hot or too cold?

	Never	Few times a year	Few times a month	Few times a week	Every day
Too hot in some room(s)					
Too cold in some room(s)					

7. How often is the kitchen range hood or kitchen exhaust fan used when cooking with the cooktop?
   a. Most of the time or always
   b. Sometimes/as needed
   c. Rarely or never

8. If the kitchen range hood or kitchen exhaust fan is NOT always used, what are the reasons for not using it? Select all that apply.
   a. Forget to turn it on
   b. Not needed for what is being cooked
   c. Too noisy
   d. Doesn't seem to remove cooking fumes or odors
   e. Open window instead
   f. Uses too much energy
   g. Other. Please describe:

9. To what extent are you satisfied or dissatisfied with your mechanical ventilation system (ERV)?
   a. Very satisfied
   b. Satisfied
   c. Neutral
   d. Unsatisfied
   e. Very unsatisfied
   f. Too soon to tell

10. If you are NOT very satisfied with your mechanical ventilation system (ERV), what are the reason(s) for dissatisfaction? Select all that apply.
   a. Too noisy
   b. Too drafty
   c. Difficult to operate
   d. Difficult to maintain
   e. Uses too much energy
   f. Brings in dust, odor, or air pollutants from outdoor
   g. Not effective

   h. Other. Please describe:
   i. Too soon to tell
   j. I'm satisfied

11. On average, how many hours per day is your home occupied by at least one person, including day and night hours?

	Fewer than 8 hours per day	8 to 12 hours per day	12 to 16 hours per day	16 to 20 hours per day	More than 20 hours per day
Weekday					
Weekend					

12. On average, how many times per week do the following activities occur inside your home?
   a. Use shower
   b. Use bath or indoor jacuzzi
   c. Use dishwasher
   d. Use washing machine
   e. Hang clothes to dry indoors
   f. Cooking on cooktop (including boiling water)
   g. Cooking in oven

13. On average, how many hours per day are windows open in your house?
   a. Summer
   b. Fall
   c. Winter
   d. Spring

14. On average, how often do you leave your bedroom windows open at night when you sleep?
   a. Summer
      i. Most of the time or always
      ii. Sometimes/as needed
      iii. Rarely or never

   b. Fall
      i. Most of the time or always
      ii. Sometimes/as needed
      iii. Rarely or never

   c. Winter
      i. Most of the time or always
      ii. Sometimes/as needed
      iii. Rarely or never

d. Spring
    i. Most of the time or always
    ii. Sometimes/as needed
    iii. Rarely or never

15. On average, how often do you leave your interior bedroom <u>door</u> open at night when you sleep?
    a. Most of the time or always
    b. Sometimes/as needed
    c. Rarely or never

16. On average, how often do the following activities occur inside your home?

	Never	Few times a year	Few times a month	Few times a week	Every day
Burn candle or incense					
Vacuuming					
Use cleaning agent for floor cleaning					
Use spray air freshener					
Use pesticide spray					
Use paints, glue, solvents (e.g., hobbies, home repairs)					
Use humidifier					
Use dehumidifier					

17. On average, how often do the following activities occur outside your home?

	Never	Few times a year	Few times a month	Few times a week	Every day
Use a grill					
Burn citronella candles or other torches					
Use a fire pit					

18. Are plug-in or stick air fresheners, or other scented decorations, used in your home?
    a. Yes
    b. No
    c. Don’t know

19. Do occupants wear shoes in your home?
    a. Most of the time or always
    b. Sometimes/as needed
    c. Rarely or never

20. How many dogs, cats, or other furry pets are in the home?

21. Do you have any aquariums inside your house? If so how many total gallons?

22. Do you use a stand-alone (portable) air filter, air purifier, or air cleaner in the home? Select all locations that apply
    a. Master bedroom
    b. Other bedroom(s)
    c. Living room
    d. Home office
    e. Other
    f. None used

23. Do you have any other items that impact indoor air quality or humidity? (E.g., fountains, indoor plants) If so, please list.

24. Has anyone in the household experienced issues with asthma while indoors in the last year?

25. Has anyone in the household experienced issues with allergies while indoors in the last year?

<u>Seasonal Survey</u>

This survey was presented to each homeowner online two times per season (timed so that one survey corresponds with each ventilation mode toggle, for a total of eight surveys). The homeowner was not informed which mode they were answering questions about.

Please answer the following three questions about the comfort inside your home the last seven days.

1. How satisfied were you with the general comfort inside your home over the past week?
    a. Very satisfied
    b. Satisfied
    c. Neutral
    d. Unsatisfied
    e. Very unsatisfied

2. How satisfied were you with the air quality (odors, stuffiness, allergens) in your home over the past week?
    a. Very satisfied
    b. Satisfied
    c. Neutral
    d. Unsatisfied
    e. Very unsatisfied

If you answered "unsatisfied" or "very unsatisfied" to any of the above, were there any particular days that stood out?

3. How humid or dry did your home feel last week?
    a. Very humid
    b. Humid
    c. Neutral
    d. Dry
    e. Very dry
    f. It fluctuated. Please describe:

Appendix B: Supplementary IAQ Analysis Results

Additional IAQ Result Figures

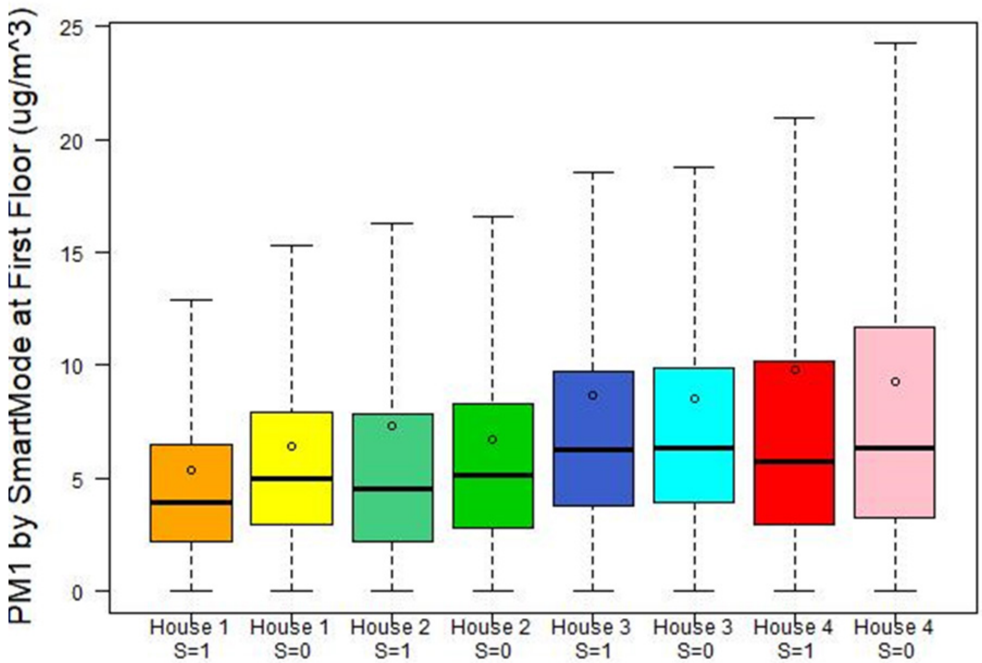

Figure 29. PM_1 results on the first floor by ERV mode
(S = 1 refers to ERV Smart Mode; S = 0 refers to ERV Continuous Mode)

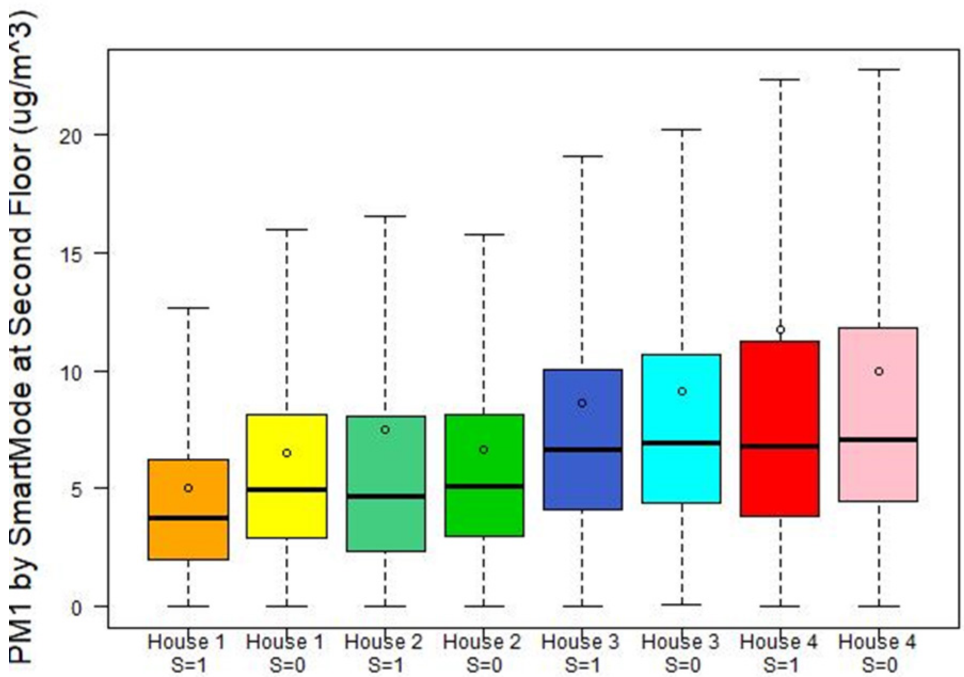

Figure 30. PM_1 results on the second floor by ERV mode
(S = 1 refers to ERV Smart Mode; S = 0 refers to ERV Continuous Mode)

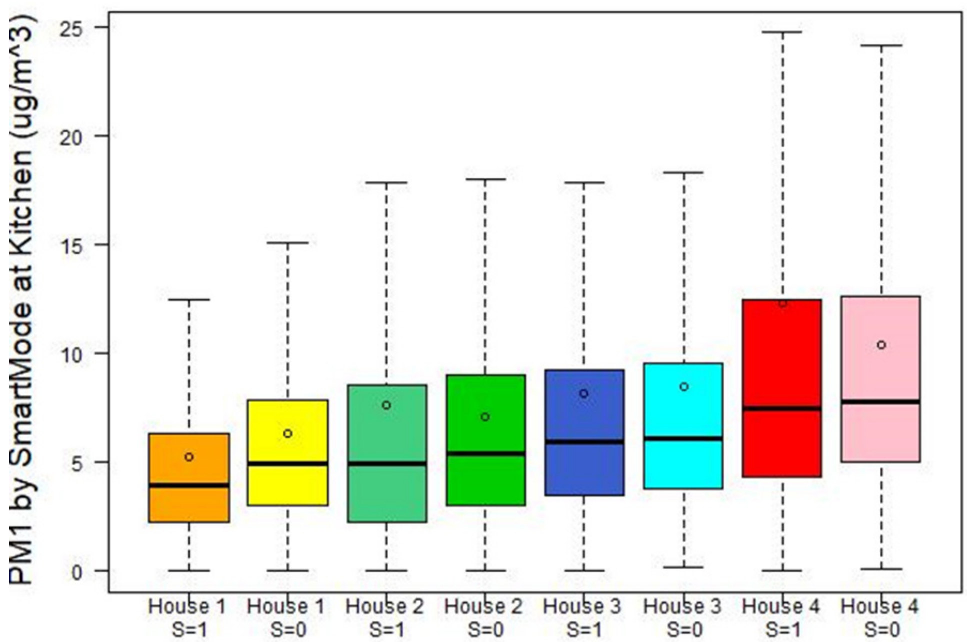

Figure 31. PM_1 results in the kitchen by ERV mode
(S = 1 refers to ERV Smart Mode; S = 0 refers to ERV Continuous Mode)

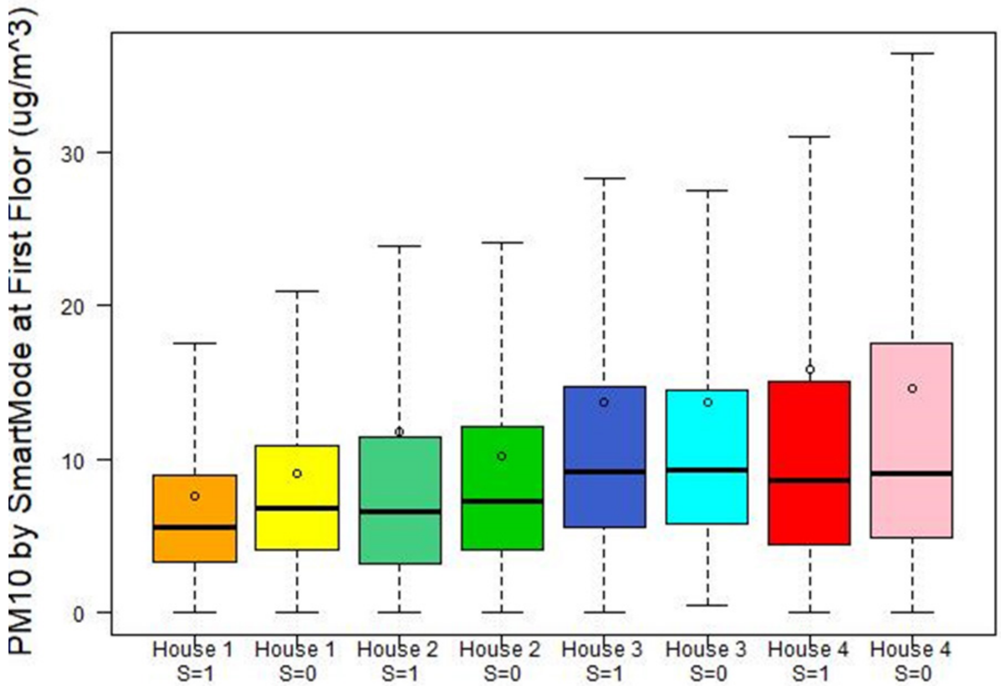

Figure 32. PM_{10} results on the first floor by ERV mode
(S = 1 refers to ERV Smart Mode; S = 0 refers to ERV Continuous Mode)

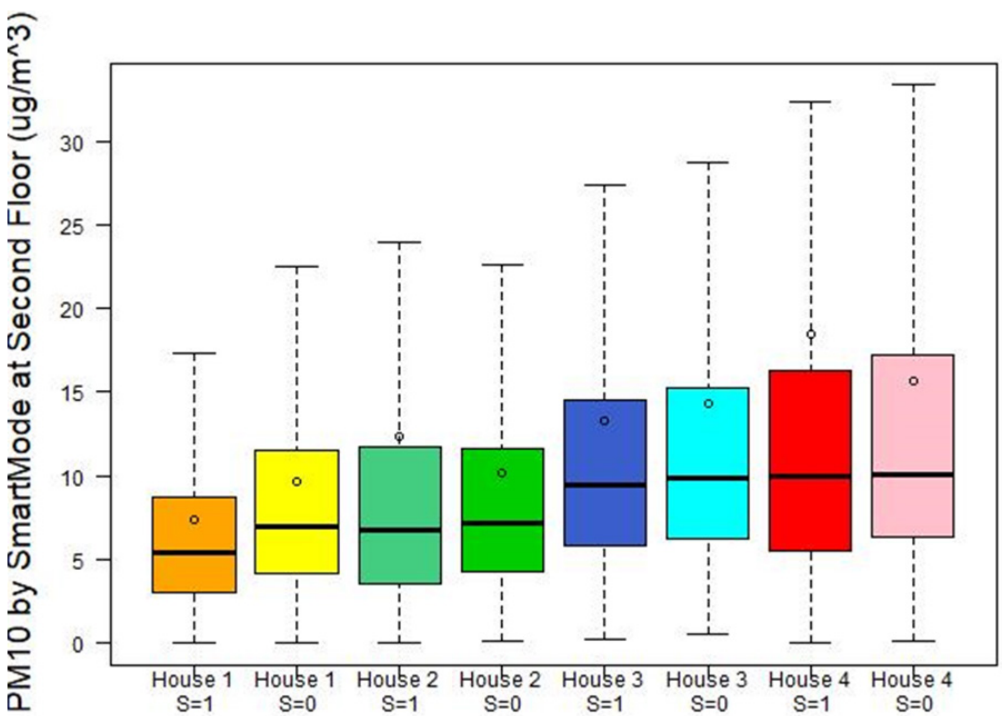

Figure 33. PM_{10} results on the second floor by ERV mode
(S = 1 refers to ERV Smart Mode; S = 0 refers to ERV Continuous Mode)

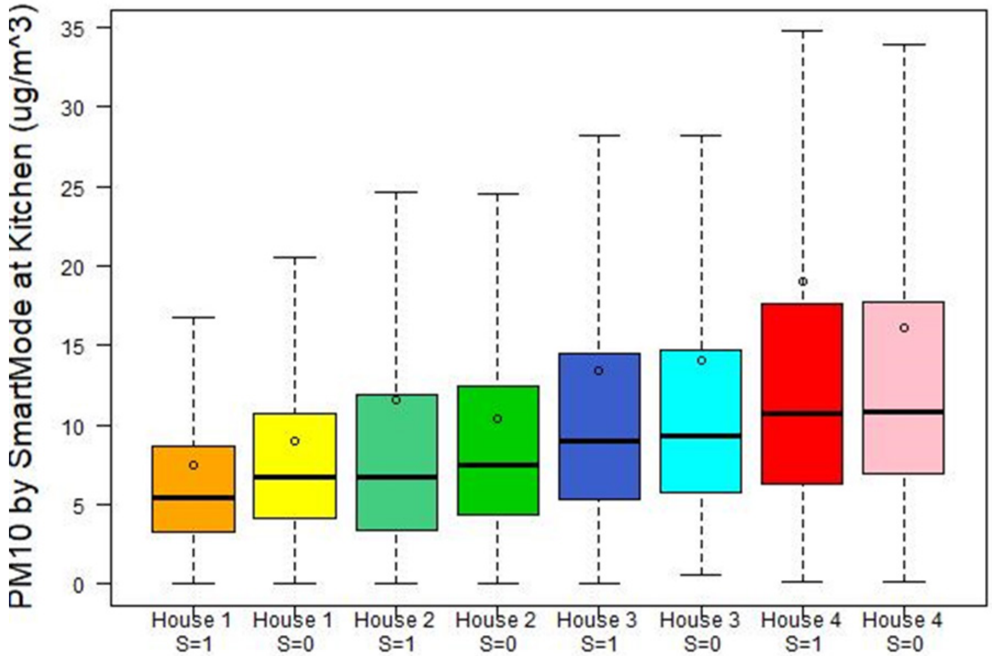

Figure 34. PM_{10} results in the kitchen by ERV mode
(S = 1 refers to ERV Smart Mode; S = 0 refers to ERV Continuous Mode)

Regression Models and Result Details

$PM_{2.5}$ Model 1

```
> #pm25
> glmpm25_1<-glmmPQL(value~smart+outdoor+microenv+temp+hd+household, random=~
1|Date,correlation =
corAR1(form=~1|Date), family=gaussian, data=sflongpm25)
iteration 1
iteration 2
> summary(glmpm25_1)
Linear mixed-effects model fit by maximum likelihood
 Data: sflongpm25
  AIC BIC logLik
   NA  NA     NA

Random effects:
 Formula: ~1 | Date
        (Intercept) Residual
StdDev:     6.09542 15.57581

Correlation Structure: AR(1)
 Formula: ~1 | Date
 Parameter estimate(s):
      Phi
0.7074984
Variance function:
 Structure: fixed weights
 Formula: ~invwt
Fixed effects: value ~ smart + outdoor + microenv + temp + hd + household
                        Value Std.Error    DF   t-value p-value
(Intercept)          9.453768  4.003263 77495  2.361516  0.0182
smart               -0.774085  0.410412 77495 -2.086115  0.0493
outdoor              0.183886  0.010372 77495 17.729650  0.0000
microenvkitchen      0.705641  0.273942 77495  2.575877  0.0100
microenvsecondfloor  0.247986  0.268237 77495  0.924502  0.3552
temp                -0.089414  0.047423 77495 -1.885442  0.0594
hd                   0.077273  0.033901 77495  2.279341  0.0226
householdh2          2.700382  0.267711 77495 10.086925  0.0000
householdh3          5.938680  0.290367 77495 20.452348  0.0000
householdh4          5.890742  0.299031 77495 19.699467  0.0000
 Correlation:
                    (Intr) smart  outdor mcrnvk mcrnvs temp   hd     hshld2 h
shld3
smart               -0.052
outdoor             -0.064  0.025
microenvkitchen     -0.034  0.000 -0.001
microenvsecondfloor -0.041  0.000  0.002  0.521
temp                -0.915 -0.008  0.027  0.001  0.007
hd                  -0.467 -0.002  0.039  0.000 -0.003  0.093
householdh2         -0.047  0.004  0.000 -0.028  0.020  0.024 -0.006
householdh3         -0.053  0.007  0.001 -0.051  0.054  0.028 -0.005  0.522
householdh4         -0.034  0.002 -0.001 -0.041 -0.018  0.004  0.007  0.375
0.451
```

```
Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-2.60179487 -0.28880312 -0.10342689  0.08619589 42.73024179

Number of Observations: 77869
Number of Groups: 365
```

Key Point: The regression model run above consists of a linear mixed effect model with random intercepts for each field sampling date, with control for autoregressive correlation between each sampling date. When adjusting for covariates including outdoor $PM_{2.5}$ concentrations, microenvironment (e.g., first floor, second floor, kitchen), indoor temperature and humidity, as well as household (e.g., household 1, 2, 3, or 4), indoor $PM_{2.5}$ concentration was 0.77 ug/m^3 lower (p=0.049) when using smart mode, compared to ERV continuous mode.

$PM_{2.5}$ Model 2: Here, different households were modeled as a random effects rather than as a fixed effects in model 1.

```
> glmpm25_2<-glmmPQL(value~smart+outdoor+microenv+temp+hd, random=list(Date =
~1,household= ~1),correlation =
corAR1(form=~1|Date), family=gaussian, data=sflongpm25)
iteration 1
iteration 2
> summary(glmpm25_2)
Linear mixed-effects model fit by maximum likelihood
 Data: sflongpm25
  AIC BIC logLik
   NA  NA     NA

Random effects:
 Formula: ~1 | Date
        (Intercept)
StdDev:    5.180754

 Formula: ~1 | household %in% Date
        (Intercept) Residual
StdDev:    8.124888 14.20578

Correlation Structure: AR(1)
 Formula: ~1 | Date/household
 Parameter estimate(s):
      Phi
0.6702258
Variance function:
 Structure: fixed weights
 Formula: ~invwt
Fixed effects: value ~ smart + outdoor + microenv + temp + hd
                         Value Std.Error    DF   t-value p-value
(Intercept)           7.778283  3.940303 76617  1.974032  0.0484
smart                -0.840580  0.414277 76617 -2.029031  0.0425
outdoor               0.178730  0.010138 76617 17.629481  0.0000
microenvkitchen       0.473011  0.213748 76617  2.212933  0.0269
```

```
microenvsecondfloor -0.071292  0.222507 76617 -0.320402  0.7487
temp                -0.024887  0.046946 76617 -0.530113  0.5960
hd                   0.088789  0.033209 76617  2.673626  0.0075
 Correlation:
                    (Intr) smart  outdor mcrnvk mcrnvs temp
smart               -0.054
outdoor             -0.060  0.023
microenvkitchen     -0.026 -0.001 -0.001
microenvsecondfloor -0.037 -0.002  0.002  0.438
temp                -0.916 -0.008  0.025 -0.001  0.010
hd                  -0.464  0.003  0.035  0.001  0.004  0.090

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-6.05289474 -0.20784753 -0.07798249  0.06397974 44.83391955

Number of Observations: 77869
Number of Groups:
               Date household %in% Date
                365                1246
```

Key Point: The regression model run above consists of a linear mixed effect model with random intercepts for each field sampling date and for each household, with control for autoregressive correlation between each sampling date. When adjusting for covariates including outdoor $PM_{2.5}$ concentrations, microenvironment (e.g., first floor, second floor, kitchen), indoor temperature and humidity, indoor $PM_{2.5}$ concentration was 0.84 ug/m^3 lower (p=0.043,) while using smart mode, compared to continuous mode ERV operation.

PM_1 Model 1

```
> #Total

> #pm1
> glmpm1_1<-glmmPQL(value~smart+outdoor+microenv+temp+hd+household, random=~1
|Date,correlation = corAR1(form=~1|Date), family=gaussian, data=sflongpm1)
iteration 1
iteration 2
> summary(glmpm1_1)
Linear mixed-effects model fit by maximum likelihood
 Data: sflongpm1
  AIC BIC logLik
   NA  NA     NA

Random effects:
 Formula: ~1 | Date
        (Intercept) Residual
StdDev:    4.348775 9.617953

Correlation Structure: AR(1)
 Formula: ~1 | Date
```

```
 Parameter estimate(s):
      Phi
0.7637475
Variance function:
 Structure: fixed weights
 Formula: ~invwt
Fixed effects: value ~ smart + outdoor + microenv + temp + hd + household
                         Value Std.Error    DF   t-value p-value
(Intercept)           4.563082 2.5131073 71474  1.815713  0.0694
smart                -0.552380 0.2584454 71474 -2.137319  0.0326
outdoor               0.186754 0.0084511 71474 22.098200  0.0000
microenvkitchen       0.490422 0.1832928 71474  2.675621  0.0075
microenvsecondfloor   0.176480 0.1688613 71474  1.045118  0.2960
temp                 -0.012625 0.0298946 71474 -0.422326  0.6728
hd                    0.023623 0.0205410 71474  1.150015  0.2501
householdh2           1.502091 0.1617948 71474  9.283928  0.0000
householdh3           3.992327 0.2007584 71474 19.886225  0.0000
householdh4           3.730623 0.1862564 71474 20.029500  0.0000
 Correlation:
                    (Intr) smart  outdor mcrnvk mcrnvs temp   hd     hshld2 h
shld3
smart               -0.053
outdoor             -0.061  0.027
microenvkitchen     -0.031 -0.001 -0.001
microenvsecondfloor -0.040  0.000  0.002  0.513
temp                -0.920 -0.006  0.024 -0.003  0.006
hd                  -0.459 -0.003  0.041  0.001 -0.002  0.098
householdh2         -0.042  0.002  0.000 -0.074  0.046  0.019 -0.004
householdh3         -0.046  0.005  0.001  0.084  0.056  0.020 -0.002  0.457
householdh4         -0.033  0.000 -0.001 -0.047 -0.019  0.005  0.005  0.399
0.362

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-2.89449658 -0.31093326 -0.10852840  0.09808263 26.16197095

Number of Observations: 71848
Number of Groups: 365
```

Key Point: The regression model run here is a linear mixed effect model with random intercepts for each field sampling date, with control for autoregressive correlation between each sampling date. When adjusting for covariates including outdoor PM_1 concentrations, microenvironment (e.g., first floor, second floor, kitchen), indoor temperature and humidity, as well as household (e.g., household 1, 2, 3, or 4), indoor PM_1 concentration was 0.55 ug/m^3 lower (p=0.033, marginally significant) when using smart mode, compared to the sampling period using continuous mode.

PM_1 Model 2: Here, different households were modeled as a random effects rather than as a fixed effects in model 1.

```
> glmpm1_2<-glmmPQL(value~smart+outdoor+microenv+temp+hd, random=list(Date =
~1,household= ~1),correlation = corAR1(form=~1|Date), family=gaussian, data=s
flongpm1)
iteration 1
iteration 2
> summary(glmpm1_2)
Linear mixed-effects model fit by maximum likelihood
 Data: sflongpm1
  AIC BIC logLik
   NA  NA     NA

Random effects:
 Formula: ~1 | Date
        (Intercept)
StdDev:    3.737729

 Formula: ~1 | household %in% Date
        (Intercept) Residual
StdDev:    5.753649 8.484948

Correlation Structure: AR(1)
 Formula: ~1 | Date/household
 Parameter estimate(s):
      Phi
0.7225726
Variance function:
 Structure: fixed weights
 Formula: ~invwt
Fixed effects: value ~ smart + outdoor + microenv + temp + hd
                         Value Std.Error    DF   t-value p-value
(Intercept)          2.5763494 2.4572871 70600  1.048453  0.2944
smart               -0.6063178 0.2598855 70600 -2.333019  0.0196
outdoor              0.1772280 0.0082047 70600 21.600838  0.0000
microenvkitchen      0.2366216 0.1422152 70600  1.663827  0.0962
microenvsecondfloor -0.1120926 0.1354371 70600 -0.827636  0.4079
temp                 0.0420789 0.0292635 70600  1.437928  0.1505
hd                   0.0305114 0.0199739 70600  1.527563  0.1266
 Correlation:
                    (Intr) smart  outdor mcrnvk mcrnvs temp
smart               -0.056
outdoor             -0.057  0.025
microenvkitchen     -0.021 -0.002  0.000
microenvsecondfloor -0.040 -0.002  0.003  0.391
temp                -0.920 -0.006  0.021 -0.004  0.014
hd                  -0.463  0.001  0.035  0.001  0.004  0.105

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-8.28625602 -0.22787669 -0.07945601  0.07559322 24.09940542

Number of Observations: 71848
Number of Groups:
               Date household %in% Date
                365                1242
```

Key Point: The regression model run here is a linear mixed effect model with random intercepts for each field sampling date and for each household, with control for autoregressive correlation between each sampling date. When adjusting for covariates including outdoor PM_1 concentrations, microenvironment (e.g., first floor, second floor, kitchen), indoor temperature and humidity, indoor PM_1 concentration was 0.61 ug/m^3 lower (p=0.020, statistically significant) when using smart mode, compared to the sampling period using continuous mode.

PM_{10} Model 1

```
> #pm10
> glmpm10_1<-glmmPQL(value~smart+outdoor+microenv+temp+hd+household, random=~
1|Date,correlation = corAR1(form=~1|Date), family=gaussian, data=sflongpm10)
iteration 1
iteration 2
> summary(glmpm10_1)
Linear mixed-effects model fit by maximum likelihood
 Data: sflongpm10
  AIC BIC logLik
   NA  NA     NA

Random effects:
 Formula: ~1 | Date
        (Intercept) Residual
StdDev:    6.941505 16.02612

Correlation Structure: AR(1)
 Formula: ~1 | Date
 Parameter estimate(s):
      Phi
0.7365307
Variance function:
 Structure: fixed weights
 Formula: ~invwt
Fixed effects: value ~ smart + outdoor + microenv + temp + hd + household
                        Value Std.Error    DF   t-value p-value
(Intercept)         -7.791634  4.304279 70607 -1.810206  0.0703
smart               -0.311504  0.453884 70607 -0.686308  0.4925
outdoor              0.164126  0.009041 70607 18.153668  0.0000
microenvkitchen      0.646999  0.300447 70607  2.153456  0.0313
microenvsecondfloor  0.386945  0.292556 70607  1.322637  0.1860
temp                 0.142149  0.052114 70607  2.727633  0.0064
hd                   0.084815  0.036460 70607  2.326227  0.0200
householdh2          2.901093  0.287039 70607 10.106979  0.0000
householdh3          5.717495  0.314701 70607 18.168034  0.0000
householdh4          5.118857  0.325406 70607 15.730687  0.0000
 Correlation:
                    (Intr) smart  outdor mcrnvk mcrnvs temp   hd     hshld2 h
shld3
smart               -0.053
outdoor             -0.057  0.021
microenvkitchen     -0.034 -0.001 -0.001
microenvsecondfloor -0.042  0.000  0.002  0.523
temp                -0.915 -0.007  0.026  0.001  0.008
```

```
hd                   -0.417 -0.006  0.032 -0.001 -0.003  0.037
householdh2          -0.045  0.003  0.000 -0.035  0.022  0.022 -0.006
householdh3          -0.052  0.006  0.001 -0.060  0.063  0.026 -0.005  0.528
householdh4          -0.032  0.001 -0.001 -0.049 -0.020  0.002  0.006  0.362
0.446

Standardized Within-Group Residuals:
        Min          Q1         Med          Q3         Max
-3.51640817 -0.28253586 -0.11282424  0.07177921 48.68336347

Number of Observations: 70957
Number of Groups: 341
```

Key Point: The regression model run here is a linear mixed effect model with random intercepts for each field sampling date, with control for autoregressive correlation between each sampling date. When adjusting for covariates including outdoor PM_{10} concentrations, microenvironment (e.g., first floor, second floor, kitchen), indoor temperature and humidity, as well as household (e.g., household 1, 2, 3, or 4), indoor PM_{10} concentration was 0.31 ug/m^3 lower (p=0.493, not significant) when using smart mode, compared to the sampling period using continuous mode.

PM_{10} Model 2: Here, different households were modeled as a random effects rather than as a fixed effects in model 1.

```
>
> glmpm10_2<-glmmPQL(value~smart+outdoor+microenv+temp+hd, random=list(Date =
~1,household= ~1),correlation = corAR1(form=~1|Date), family=gaussian, data=s
flongpm10)
iteration 1
iteration 2
> summary(glmpm10_2)
Linear mixed-effects model fit by maximum likelihood
 Data: sflongpm10
  AIC BIC logLik
   NA  NA     NA

Random effects:
 Formula: ~1 | Date
        (Intercept)
StdDev:    6.107359

 Formula: ~1 | household %in% Date
        (Intercept) Residual
StdDev:    9.690279  14.1909

Correlation Structure: AR(1)
 Formula: ~1 | Date/household
 Parameter estimate(s):
     Phi
0.6891062
Variance function:
 Structure: fixed weights
 Formula: ~invwt
Fixed effects: value ~ smart + outdoor + microenv + temp + hd
```

```
                         Value Std.Error    DF   t-value p-value
(Intercept)         -10.556501  4.216973 69801 -2.503336  0.0123
smart                -0.332205  0.457287 69801 -0.726470  0.4676
outdoor               0.161248  0.008784 69801 18.357057  0.0000
microenvkitchen       0.385852  0.224465 69801  1.718989  0.0856
microenvsecondfloor   0.066886  0.234311 69801  0.285459  0.7753
temp                  0.220986  0.051317 69801  4.306291  0.0000
hd                    0.093566  0.035432 69801  2.640710  0.0083
 Correlation:
                    (Intr) smart  outdor mcrnvk mcrnvs temp
smart               -0.056
outdoor             -0.052  0.019
microenvkitchen     -0.026 -0.001 -0.001
microenvsecondfloor -0.037 -0.002  0.002  0.431
temp                -0.915 -0.006  0.022 -0.002  0.010
hd                  -0.413 -0.002  0.027  0.001  0.003  0.036

Standardized Within-Group Residuals:
         Min           Q1          Med           Q3          Max
-10.14993019  -0.20505768  -0.07148142   0.05957358  48.04402442

Number of Observations: 70957
Number of Groups:
               Date household %in% Date
                341                1150
```

Key Point: The regression model run here is a linear mixed effect model with random intercepts for each field sampling date and for each household, with control for autoregressive correlation between each sampling date. When adjusting for covariates including outdoor PM_1 concentrations, microenvironment (e.g., first floor, second floor, kitchen), indoor temperature and humidity, indoor PM_{10} concentration was 0.33 ug/m^3 lower (p=0.468, not significant) when using smart mode, compared to the sampling period using continuous mode.

Appendix C: Detailed Low-Cost IAQ Sensor Chamber Testing Results

We compiled summary statistics for the array of sensors at each chamber challenge point. These included maximum reading, minimum reading, and average of the group. The statistical comparisons included calculating the coefficient of variation (CV) and relative percent difference (RPD). The CV was calculated for the group of sensors at each challenge point to assess the variation among the individual sensors in the array. The RPD was used to assess the difference between the average of the sensors and the reference value from the laboratory instrument. RPD values were also calculated for the individual sensors and the reference value. Both CV and RPD are smaller if the data values are closer together. As measures of closeness of values 20% or below is generally regarded as acceptable for both CV and RPD.

The CV values in Table 38 for 2017 and 2019 indicate that there was minimal variation among the temperature sensors. The RPD values indicated close agreement with the reference value. This indicates acceptable performance of the temperature sensors individually and as a group.

The CV values in Table 39 for 2017 and 2019 indicate that there was minimal variation among the RH sensors. The RPD values in Table 39 indicated close agreement with the reference value, except for the third and fourth time points in 2019. The RH dropped from about 95% to 40% over approximately a 2-hour period. This rate of change of RH may have exceeded the response time of the sensors, and a longer equilibrium time may be needed to gain a fair evaluation of the agreement of the sensors with the reference instrument. This is supported by the low CV values at these time points, indicating consistency of the response in addition to the fact that at both time points the sensors were reading higher than the reference value, which is consistent with a slower response. Overall, this indicates acceptable performance of the RH sensors individually and as a group.

Table 38. Low-Cost Temperature Sensors Compared to Reference in 2017 and 2019

2017 Temperature (°F)									
Time Points	Reference Measurement	Number of Low-Cost Sensors, n	Max	Min	Average	CV	RPD Average vs. Ref.	Max RPD	# >20% RPD
1	81.0	18	82.1	80.1	80.7	0.8%	0.3%	1.5%	0
2	83.5	18	85.1	82.2	83.0	1.0%	0.7%	1.8%	0
3	85.8	18	87.7	84.8	85.7	1.0%	0.1%	2.2%	0
4	84.7	8	86.5	84.1	84.5	1.1%	0.3%	2.1%	0
2019 Temperature (°F)									
1	77.7	18	83.3	76.2	78.5	2.0%	1.0%	6.8%	0
2	74.1	18	79.0	75.5	76.8	1.3%	3.5%	6.4%	0
3	77.1	18	79.9	76.2	77.4	1.2%	0.4%	3.5%	0
4	79.2	18	81.4	77.8	79.1	1.2%	0.2%	2.8%	0

Table 39. Low-Cost Relative Humidity Sensors Compared to Reference in 2017 and 2019

2017 Relative Humidity (% RH)									
Time Points	Reference Measurement	Number of Low-Cost Sensors, n	Max	Min	Average	CV	RPD Average vs. Ref.	Max RPD	# >20% RPD
1	38.2	18	41.3	38.3	40.3	2.1%	5.3%	7.5%	0
2	46.8	18	49.2	44.9	48.0	2.4%	2.6%	5.0%	0
3	45.3	18	47.2	43.5	46.2	2.5%	2.0%	4.3%	0
4	48.4	8	50.0	46.2	49.2	2.7%	1.6%	4.6%	0
2019 Relative Humidity (% RH)									
1	42.1	17	44.7	37.7	42.3	4.7%	0.3%	11.0%	0
2	95.5	17	89.7	81.6	86.5	2.7%	10.0%	16.0%	0
3	37.3	17	60.6	54.1	57.4	2.8%	42.4%	47.6%	17
4	32.7	17	48.5	43.2	45.9	2.9%	33.4%	38.9%	17

The CV values in Table 40 for 2019 indicate that there was minimal variation among the CO_2 sensors after the field deployment. However, the 2017 values indicate a larger variation among the sensors prior to deployment. This is likely due to the Automatic Background Calibration logic (ABC Logic) that these CO_2 sensors perform, in which they recalibrate themselves when exposed to ambient (400-ppm CO_2) air. The RPD values indicate improvement after the field deployment as well, showing close agreement with the reference value in 2019 but larger variation in 2017. This indicates acceptable performance of the CO_2 sensors individually and as a group after background calibration is performed.

Table 40. Low-Cost CO_2 Sensors Compared to Reference in 2017 and 2019

Time Points	Reference Measurement	Number of Low-Cost Sensors, n	Max	Min	Average	CV	RPD Average vs. Ref.	Max RPD	# >20% RPD
2017 CO_2 (ppm)									
1	1,405	18	2,272	1,189	1,547	17.0%	9.6%	46.3%	4
2	1,276	18	2,087	1,069	1,413	17.6%	10.2%	48.3%	4
3	599	17	1,152	534	702	24.2%	15.9%	63.6%	5
4	459	8	679	389	451	23.4%	1.8%	38.6%	1
2019 CO_2 (ppm)									
1	670	17	794	685	722	3.6%	7.5%	17.2%	0
2	1,254	17	1,357	1,215	1,268	2.6%	1.1%	7.2%	0
3	2,454	17	2,705	2,461	2,568	2.4%	4.5%	6.0%	0
4	1,684	17	1,788	1,626	1,701	2.2%	1.0%	6.8%	0
5	1,020	17	1,098	984	1,024	2.6%	0.3%	8.3%	0

The values for $PM_{2.5}$ and PM_{10} were essentially the same, which is consistent with most of the PM being in the $PM_{2.5}$ size range, as expected from a combustion source.

The CV values in Table 41 and Table 42 for 2017 and 2019 indicate that there was minimal variation among the PM sensors for both $PM_{2.5}$ and PM_{10} in both 2017 and 2019. The RPD values in Table 41 and Table 42 consistently exceed 20%, showing that the sensors differ from the reference values. The values from the sensors were consistently lower than the reference value. Because the sensors and the reference instrument both are light-sensing technologies that use an algorithm to convert counts into a mass value, the difference could be attributable to differences in the algorithm.

Table 41. Low-Cost $PM_{2.5}$ Sensors Compared to Reference in 2017 and 2019

2017 $PM_{2.5}$ (ug/m^3)									
Time Points	Reference Measurement	Number of Low-Cost Sensors, n	Max	Min	Average	CV	RPD Average vs. Ref.	Max RPD	# >20% RPD
1	114	21	67	51	58	6.6%	64.7%	73.1%	21
2	60	15	44	37	40	5.7%	39.4%	43.2%	15
3	161	20	99	77	87	6.2%	60.2%	68.3%	20
4	52	14	40	29	37	6.8%	34.3%	52.6%	14
2019 $PM_{2.5}$ (ug/m^3)									
1	253	21	123	87	107	7.8%	80.9%	98.5%	21
2	125	21	70	51	61	7.6%	69.2%	84.6%	21
3	151	21	74	52	64	7.8%	80.4%	97.5%	21
4	75	21	46	34	42	7.3%	56.9%	71.9%	21

Table 42. Low-Cost PM_{10} Sensors Compared to Reference in 2017 and 2019

2017 PM_{10} (ug/m^3)									
Time Points	Reference Measurement	Number of Low-Cost Sensors, n	Max	Min	Average	CV	RPD Average vs. Ref.	Max RPD	# >20% RPD
1	114	20	76	63	70	4.5%	48.3%	55.2%	20
2	60	20	53	43	48	5.9%	21.9%	28.6%	10
3	161	22	102	82	91	5.4%	56.0%	62.1%	22
4	52	15	47	36	43	6.0%	18.4%	33.7%	6
2019 PM_{10} (ug/m^3)									
1	254	21	145	103	125	8.2%	68.06%	91.7%	21
2	125	21	82	67	74	5.2%	50.8%	69.8%	21
3	151	21	77	57	69	7.2%	74.4%	95.6%	21
4	75	21	63	46	54	8.0%	32.3%	54.2%	21

Figure 35 plots the average PM_{10} concentration of the low-cost sensors and the reference PM_{10} values from 2017. Although the value of the sensors was consistently lower than the reference, the trends were very similar as shown by a r =0.976 correlation coefficient.

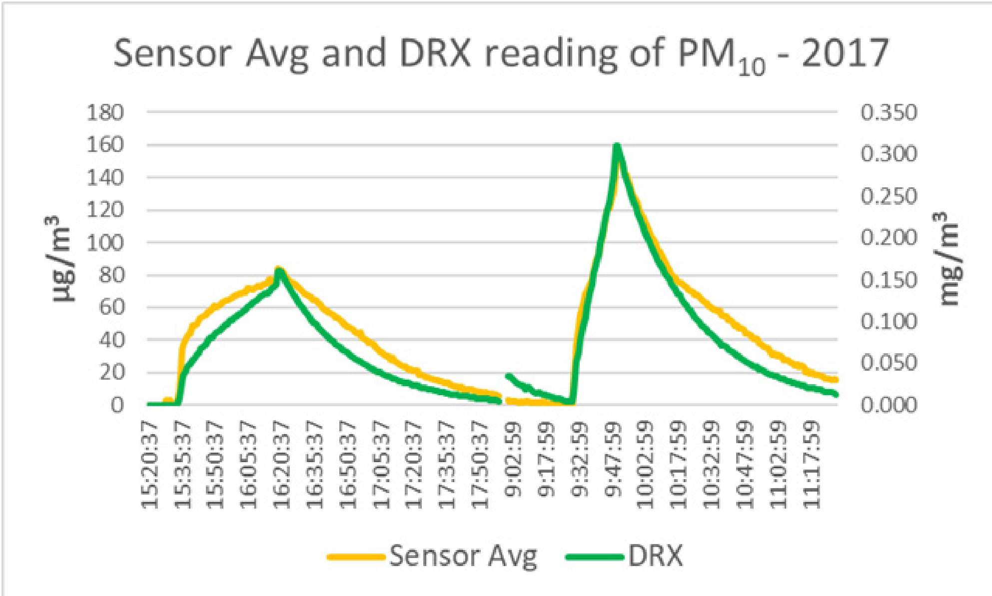

Figure 35. Low-cost sensor average and DustTrak (DRX) correlation for PM_{10} in 2017

Figure 36 plots the average PM_{10} concentration of the low-cost sensors and the reference PM_{10} values from 2019. Although the value of the sensors was consistently lower than the reference, the trends were very similar, as shown by a r=0.986 correlation coefficient.

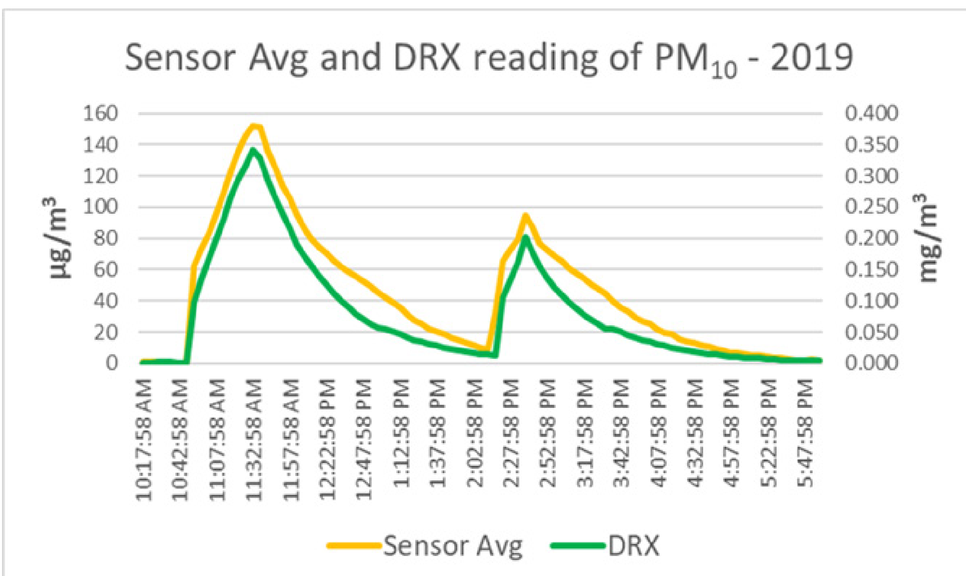

Figure 36. Low-cost sensor average and DustTrak (DRX) correlation for PM_{10} in 2019

The strong correlation between the averaged sensor value and the reference value indicates that adjustments to the sensor values would be valid corrections, at least for this data set. The percentage of the reference value represented by the sensor average was calculated for the time periods of the peaks in Figure 35 and Figure 36.

Figure 37 plots the distribution of these percentage values. The median values are 73% and 64% for 2017 and 2019, respectively.

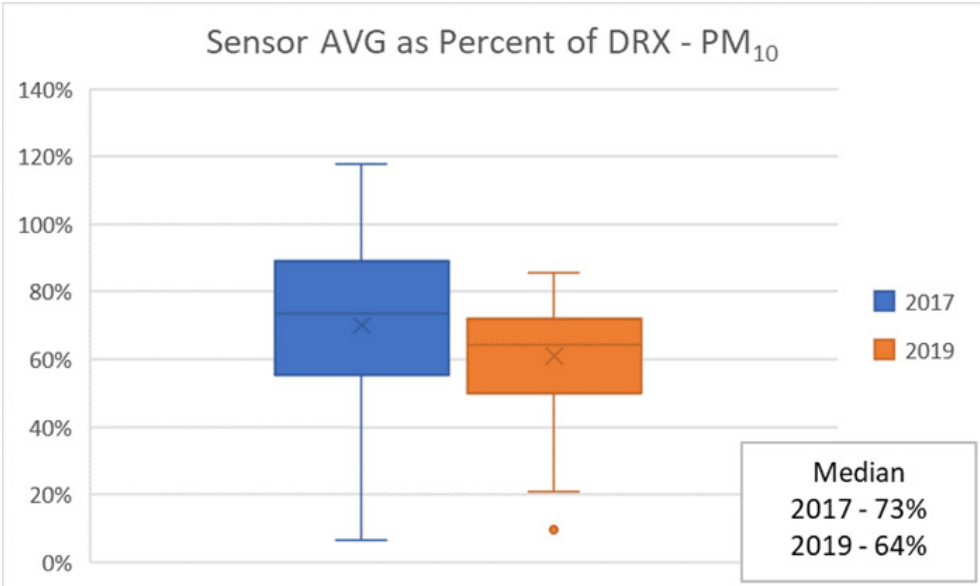

Figure 37. Box and whisker plots of sensor group average PM_{10} as a percentage of reference (DustTrak, or DRX) PM_{10} value in 2017 (n=146) and 2019 (n=93)

Although the sensors consistently reported lower values than the reference instrument, the difference was reasonably consistent. Thus, adjustments could be made if desired. Coupled with the relatively tight CV values for the sensors as a group, this indicates a qualified acceptable performance of the PM sensors individually and as a group.

Appendix D: Additional BEopt Modeling Assumptions and Model Result Corrections

Following are the additional BEopt modeling assumptions used in each of the four houses.

House 1:

- Assumed front and back door is 100% glass
- Attic insulation: R-30 based off on-site assessment
- Interior shading: summer = 0.7, winter = 0.7
- Ceiling fan: national average
- Water heating distribution: R-2 Trunk Branch, PEX
- Interzonal floor: R-30, Grade I (based off original builder plans)
- Distance from neighbors: left/right @ 25 ft
- Floor covering: percentage of carpet for each house assumed to be 40%
- Lighting: 100% compact fluorescent lamp (CFL) bulbs.

Houses 2–3:

- Assumed front and back door is 100% glass
- Attic insulation: R-30 based off on-site assessment
- Interior shading: summer = 0.7, winter = 0.7
- Ceiling fan: national average
- Water heating distribution: R-2 Trunk Branch, PEX
- Interzonal floor: R-30, Grade I (based off original builder plans)
- Distance from neighbors: left/right @ 25 ft
- Floor covering: percentage of carpet for each house assumed to be 60%.

House 4:

- Assumed front and back door is 100% glass
- Attic insulation: R-30 based off on-site assessment
- Interior shading: summer = 0.7, winter = 0.7
- Ceiling fan: national average
- Water heating distribution: R-2 Trunk Branch, PEX
- Interzonal floor: R-30, Grade I (based off original builder plans)
- Distance from neighbors: right @ 25 ft
- Floor covering: percentage of carpet for each house assumed to be 60%

As mentioned in Section 2.3: Analysis Methods and Section 3.4: Energy Analysis Results, the raw output from BEopt for the ERV-option models contained errors, so the values presented in the body of the report were corrected using calculations external to BEopt. The raw kWh results for the five ventilation options can be seen in Figure 38, and the therm results can be seen in Figure 39. The tabulated results can be seen in Table 43 and Table 44, compared to the B10 benchmark. The values that were corrected for the body of the report are in red in the tables.

In every house, as expected, the models with the smart ERV used less electricity than that same ERV running continuously. However, the two CFIS houses used less energy than the smart or continuous ERV mode models. Additionally, the gas usage output showed the two CFIS options using less than any of the ERV options. These unexpected results led us to further investigate the model outputs.

After investigation, the specific issues identified with the BEopt model results were as follows (calculation examples are given for House 1, but a similar comment applies to each house):

1. We created the ERV Options using measured and spec'd values so that the "Continuous ERV" was 100.5 W at 93 cfm, and the "Continuous ERV at Q_{fan}" was 41.6 W at 58 cfm. However, the Vent Fan results show a 774-kWh difference between the two units, even though 8,760-hr runtimes for each unit wattage should give about a 515-kWh difference.
2. The Cooling usage is lower for "CFIS at Q_{fan}" than for "Continuous ERV at Q_{fan}." We expected the ERV energy recovery would cause the cooling load to be lower at the same OA levels.
3. The Heating usage is lower for "CFIS at Q_{fan}" than for "Continuous ERV at Q_{fan}." We expected the ERV energy recovery would cause the heating load to be lower at the same OA levels.
4. Additionally, the difference between "Continuous ERV" and "Continuous ERV at Q_{fan}" Cooling is 170 kWh, but the difference between "CFIS at Q_{tot}" and "CFIS at Q_{fan}" Cooling is 41 kWh. It is a 40-cfm OA difference between the models in both cases, only the ERV models have heat recovery for the OA. Therefore, we would expect the cooling load differential for the CFIS models to be at least the same as the ERV models, if not higher.

We believe that the bug in the software centers around the treatment of the ERV fan energy usage and the ERV sensible load induction calculations. As a result of the discovery of these errors, we made the following adjustments and corrections to the BEopt ERV model output, presented in the Energy Analysis Results section:

1. The ERV fan energy usage was calculated using the fan total wattage and the BEopt-predicted run hours for smart mode and 8,760 hours for continuous.
2. The Cooling, Cooling Fan, and Heating Fan electricity and Heating gas usage were estimated for the "Continuous ERV" and "Continuous ERV at Q_{fan}" models by using the

Supply modeling option and reducing the Supply OA flow rate to correspond to the sensible load reduction afforded be the ERV. For example, for the House 1 "Continuous ERV at Q_{fan}" model, the Q_{fan} rate of 58 cfm was multiplied times (1-0.64) to yield 20.9 cfm, where 0.64 is the Sensible Recovery Efficiency of the ERV at that flow rate.

3. The Smart ERV Cooling, Cooling Fan, and Heating Fan electricity and the Heating gas usage were estimated using the corrected "Continuous ERV" results in (2) above, multiplied by the original ratio of the raw BEopt Smart ERV to Continuous ERV outputs (0.95 for electricity and 0.99 for gas).

The combination of the above corrections can be seen in Section 3.4 in the body of the report.

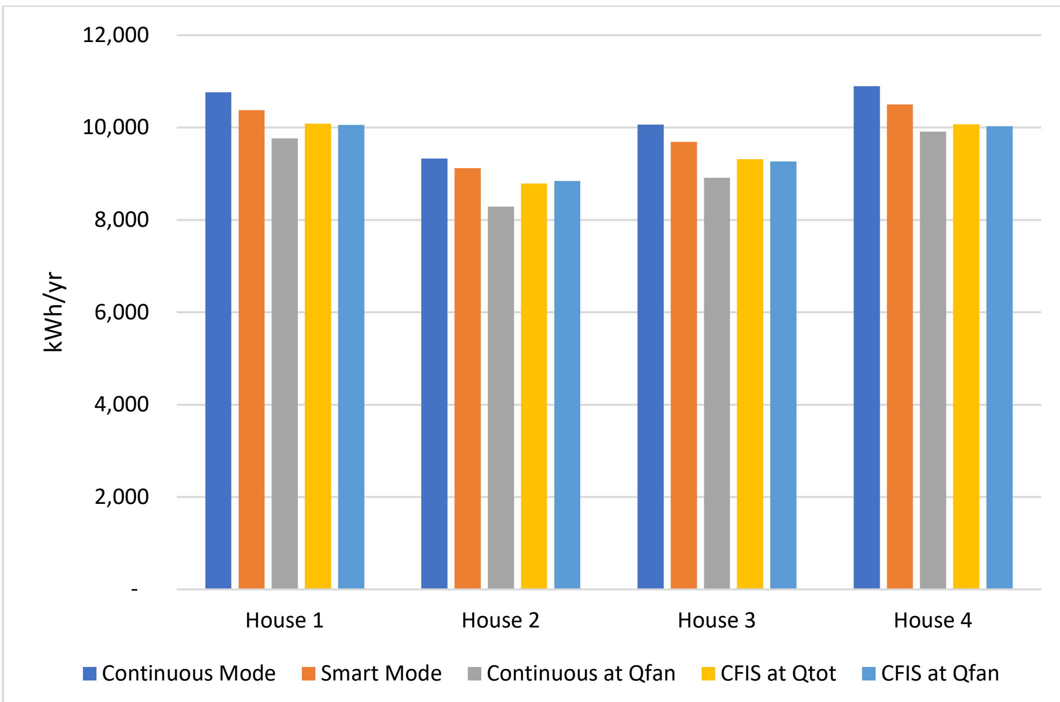

Figure 38. Uncorrected BEopt model annual kWh usage results for the five ventilation options

Figure 39. Uncorrected BEopt model annual therm usage results for the five ventilation options

Table 43. Uncorrected BEopt Model Annual kWh Usage Results by End Use for the Five Ventilation Options

	End Use	B10 Bench-mark	Continuous ERV	Smart ERV	Continuous ERV at Q_{fan}	CFIS at Q_{tot}	CFIS at Q_{fan}
House 1	Misc.	2,664.1	2,664.1	2,664.1	2,664.1	2,664.1	2,664.1
	Vent Fan	105.5	1,345.3	1,128.4	571.5	849.9	861.7
	Large Appliances	2,394.5	2,045.7	2,045.7	2,045.7	2,045.7	2,045.7
	Lights	1,972.5	1,263.2	1,263.2	1,263.2	1,263.2	1,263.2
	Cooling Fan/Pump	621.3	624.3	592.0	577.4	589.1	586.2
	Heating Fan/Pump	228.6	58.6	58.6	52.8	49.8	49.8
	Cooling	2,558.6	2,737.4	2,596.7	2,567.4	2,599.7	2,558.6
	Hot Water	-	26.4	26.4	26.4	26.4	26.4
	Total	**10,545**	**10,765**	**10,375**	**9,768**	**10,088**	**10,056**
House 2	Misc.	2,464.8	2,464.8	2,464.8	2,464.8	2,464.8	2,464.8
	Vent Fan	90.9	1,336.5	1,219.2	507.0	1,084.4	1,084.4
	Large Appliances	2,116.1	680.0	680.0	680.0	680.0	680.0

	End Use	B10 Bench-mark	Continuous ERV	Smart ERV	Continuous ERV at Q_{fan}	CFIS at Q_{tot}	CFIS at Q_{fan}
	Lights	1,931.4	1,066.8	1,066.8	1,066.8	1,066.8	1,066.8
	Cooling Fan/Pump	512.9	873.4	852.9	814.8	791.3	806.0
	Heating Fan/Pump	381.0	114.3	114.3	111.4	99.7	102.6
	Cooling	1,943.1	2,766.7	2,699.3	2,623.1	2,576.2	2,614.3
	Hot Water	-	23.5	23.5	23.5	23.5	23.5
	Total	**9,440**	**9,326**	**9,121**	**8,291**	**8,787**	**8,842**
	End Use	**B10 Bench-mark**	**Continuous ERV**	**Smart ERV**	**Continuous ERV at Q_{fan}**	**CFIS at Q_{tot}**	**CFIS at Q_{fan}**
House 3	Misc.	2,623.1	2,623.1	2,623.1	2,623.1	2,623.1	2,623.1
	Vent Fan	105.5	1,357.0	1,137.2	463.1	864.6	861.7
	Large Appliances	2,394.5	1,975.4	1,975.4	1,975.4	1,975.4	1,975.4
	Lights	1,890.4	1,043.4	1,043.4	1,043.4	1,043.4	1,043.4
	Cooling Fan/Pump	609.6	553.9	527.6	495.3	495.3	483.6
	Heating Fan/Pump	216.9	64.5	64.5	55.7	52.8	49.8
	Cooling	2,511.7	2,417.9	2,294.8	2,230.4	2,236.2	2,204.0
	Hot Water	-	26.4	26.4	26.4	26.4	26.4
	Total	**10,352**	**10,062**	**9,692**	**8,913**	**9,317**	**9,267**
House 4	Misc.	2,634.8	2,634.8	2,634.8	2,634.8	2,634.8	2,634.8
	Vent Fan	105.5	1,339.4	1,125.4	595.0	767.9	767.9
	Large Appliances	2,394.5	1,864.0	1,864.0	1,864.0	1,864.0	1,864.0
	Lights	1,913.8	1,544.6	1,544.6	1,544.6	1,544.6	1,544.6
	Cooling Fan/Pump	618.4	603.8	574.4	556.9	559.8	551.0
	Heating Fan/Pump	225.7	87.9	87.9	82.1	79.1	76.2
	Cooling	2,541.0	2,793.1	2,640.7	2,611.4	2,596.7	2,567.4
	Hot Water	-	26.4	26.4	26.4	26.4	26.4
	Total	**10,434**	**10,894**	**10,498**	**9,915**	**10,073**	**10,032**

Table 44. Uncorrected BEopt Model Annual Therm Usage Results by End Use for the Five Ventilation Options

	End Use	B10 Bench-mark	Continuous ERV	Smart ERV	Continuous ERV at Q_{fan}	CFIS at Q_{tot}	CFIS at Q_{fan}
House 1	Heating	316.0	179.9	179.6	164.6	156.3	151.3
	Hot Water	170.3	115.3	115.3	115.3	115.3	115.3
	Large Appliances	0.0	17.8	17.8	17.8	17.8	17.8
	Total	**486.3**	**313.0**	**312.7**	**297.7**	**289.4**	**284.4**
House 2	Heating	512.4	343.9	343.8	330.0	297.9	304.4
	Hot Water	161.5	95.2	95.2	95.2	95.2	95.2
	Large Appliances	0.0	58.3	58.3	58.3	58.3	58.3
	Total	**673.9**	**497.4**	**497.3**	**483.5**	**451.4**	**457.9**
House 3	Heating	302.6	195.0	194.6	171.1	158.5	152.4
	Hot Water	176.8	105.4	105.4	105.4	105.4	105.4
	Large Appliances	0.0	17.8	17.8	17.8	17.8	17.8
	Total	**479.4**	**318.2**	**317.8**	**294.3**	**281.7**	**275.6**
House 4	Heating	312.8	266.4	264.4	243.6	231.9	226.6
	Hot Water	176.8	110.7	110.7	110.7	110.7	110.7
	Large Appliances	0.0	17.8	17.8	17.8	17.8	17.8
	Total	**489.6**	**394.9**	**392.9**	**372.1**	**360.4**	**355.1**

Appendix E: Additional In-Situ ERV Performance Results

Table 45 and Figure 40 show how the annual average induced water vapor flow rate relates to the net flow rate of the installed ERV. It appears to be an exponential relationship, where the greater the negative net airflow, the greater the average induced water vapor flow rate. A net-positive ERV is preferable to a net-negative ERV in a climate such as Charleston with high sensible and latent loads.

Table 45. Test Home ERV-Induced cfm Infiltration vs. Annual Average Induced Water Vapor Flow Rate (lbs/hr)

	ERV-Induced cfm Infiltration	Continuous Mode Average Water Vapor Flow Rate (lbs/hr)	Smart Mode Average Water Vapor Flow Rate (lbs/hr)
House 1	-18.37	0.99	0.81
House 2	-14.83	0.61	0.52
House 3	8.26	0.5	0.35
House 4	-10.66	0.56	0.53

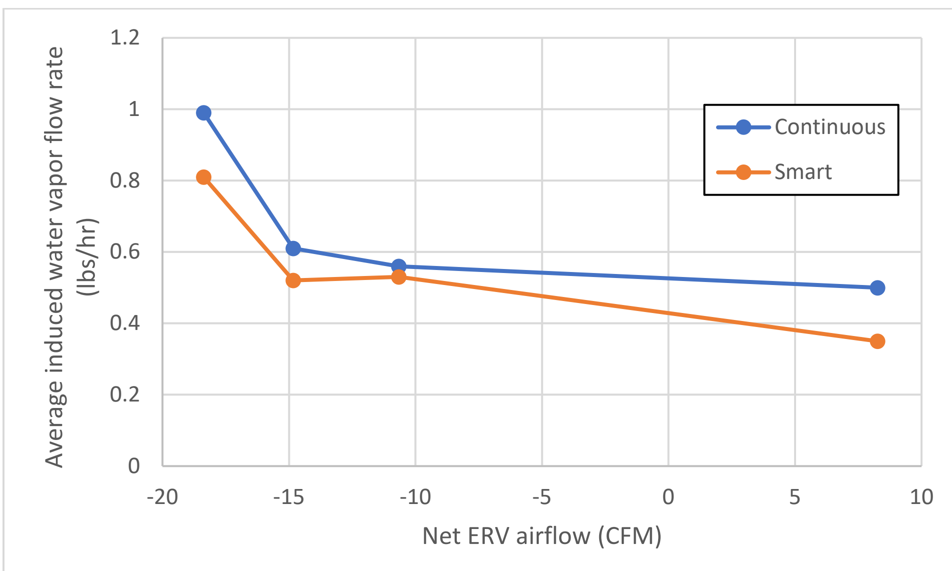

Figure 40. Test home net ERV airflow vs. annual average induced water vapor flow rate

The effect of an ERV being unbalanced in Charleston's climate can be seen in Table 46 and Figure 41. The net airflow drawn in through leaks in the building envelope results in about 100 gallons/yr of extra moisture in the building for only -10 cfm of air differential. This escalates to about 350 gallons/yr at -20 cfm of airflow differential. Smart mode aids the situation some by reducing the runtime of the ERV during the periods of highest humidity, thereby avoiding between 11% and 17% of the extra moisture.

A net-positive ERV will exhaust the differential air through the same leaks in the building envelope, but there is little difference between that and exhausting it through the ERV return duct. Taken to the extreme, however, a highly positive ERV will have degradation in load reduction capacity of the ERV; as the exhaust air approaches zero, the load reduction capacity will also approach zero (Kosar 2016).

Table 46. Total Difference in Induced Water Vapor Load in Gallons/yr Between "Actual" (As-Installed, Unbalanced) and "Ideal" (Balanced) ERV

	Net cfm	Continuous Mode	Smart Mode	% Difference
House 1	-18.37	367.6	304.6	17.1%
House 2	-14.83	241.6	199.6	17.4%
House 3	8.26	0.0	0.0	0%
House 4	-10.66	94.5	84.0	11.1%

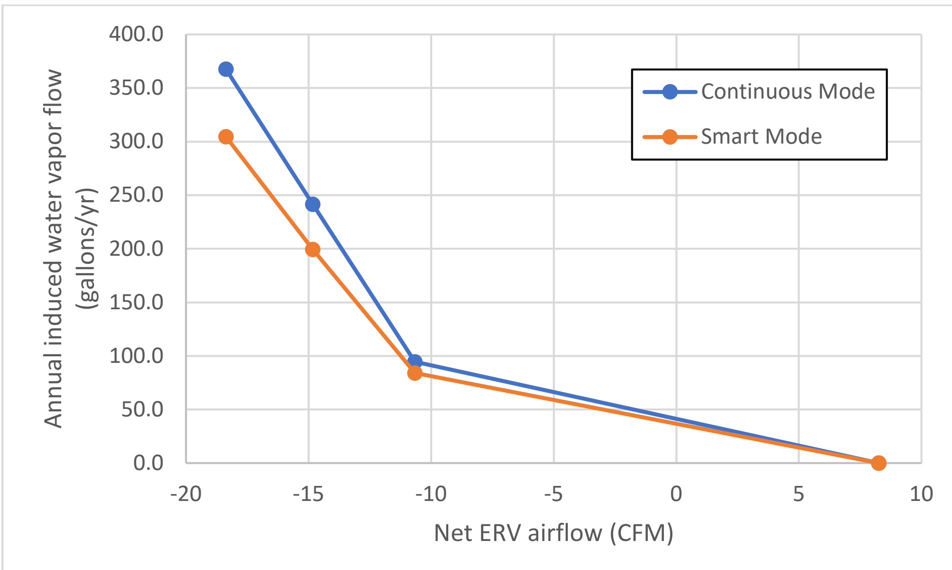

Figure 41. Test home net ERV airflow vs. average induced water vapor flow rate

Table 47 and Table 48 show how the actual and ideal ERV-induced loads vary by season. In Charleston's climate, the net latent load is positive for every season except winter. The net sensible load is positive in spring and summer, but negative in fall and winter.

Table 47. Test Home Seasonal ERV-Induced Loads (Actual)

		Spring		Summer		Fall		Winter	
Metric	**House**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**
Average Induced Water Vapor Flow rate (lbs/hr)	House 1	1.01	0.94	2.23	1.99	0.65	0.39	0.06	-0.08
	House 2	0.60	0.53	1.57	1.19	0.35	0.54	-0.07	-0.17
	House 3	0.53	0.49	1.47	1.18	0.22	0.00	-0.21	-0.29
	House 4	0.62	0.56	1.67	1.37	0.06	0.40	-0.11	-0.20
Average Induced Latent Load (Btu/hr)	House 1	1,059.6	991.2	2,347.7	2,097.1	685.9	411.0	61.7	-78.9
	House 2	635.1	561.1	1,655.7	1,250.5	363.8	564.6	-78.3	-174.0
	House 3	555.5	516.1	1,552.7	1,242.9	231.6	4.4	-218.3	-305.7
	House 4	649.3	593.7	1,760.3	1,441.5	65.4	418.7	-114.6	-211.3
Average Induced Sensible Load (Btu/hr)	House 1	313.1	271.9	708.5	658.6	-64.4	-86.9	-326.3	-368.3
	House 2	141.2	125.0	449.0	325.4	-115.0	26.3	-306.3	-365.0
	House 3	133.3	109.8	413.9	313.4	-137.8	-129.5	-337.1	-357.3
	House 4	-47.3	33.7	484.1	369.6	-373.5	-130.8	-538.7	-583.5

Table 48. Test Home Seasonal ERV-Induced Loads (Ideal)

		Spring		Summer		Fall		Winter	
Metric	**House**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**
Average Induced Water Vapor Flow rate (lbs/hr)	House 1	0.64	0.60	1.50	1.33	0.40	0.23	0.00	-0.09
	House 2	0.39	0.35	1.08	0.81	0.15	0.31	-0.11	-0.16
	House 3	0.53	0.49	1.47	1.18	0.22	0.00	-0.21	-0.29
	House 4	0.69	0.63	1.30	1.06	0.01	0.29	-0.12	-0.19
Average Induced Latent Load (Btu/hr)	House 1	676.1	636.8	1,580.6	1,403.8	424.4	242.1	-0.4	-97.3
	House 2	414.1	365.6	1,134.9	856.2	157.6	328.7	-115.6	-172.6
	House 3	555.5	516.1	1,552.7	1,242.9	231.6	4.4	-218.3	-305.7
	House 4	731.2	658.3	1,369.1	1,118.8	11.7	306.4	-127.3	-203.9
Average Induced Sensible Load (Btu/hr)	House 1	240.0	204.8	501.4	463.9	-14.0	-36.5	-187.6	-213.4
	House 2	134.3	365.6	337.3	247.1	-83.6	29.4	-166.7	-208.9
	House 3	133.3	109.8	413.9	313.4	-137.8	-129.5	-337.1	-357.3
	House 4	110.5	118.4	396.1	302.0	-272.7	-75.1	-398.8	-429.9

In-situ ERV effectiveness was calculated for each of the test homes throughout the year. The annual averages of apparent sensible effectiveness, latent effectiveness, and total effectiveness can be seen in Table 49. The effectiveness metrics are very similar for both continuous and smart modes, which was expected. Figure 42 shows how the net-positive and net-negative ERV balance affects average total effectiveness (higher exhaust to supply ratio leads to lower effectiveness). This compares favorably with the lab-tested results in Figure 43 (Kosar 2016).

Table 49. Test Home Annual ERV Effectiveness Results

	House	Continuous Mode	Smart Mode
Apparent Sensible Effectiveness	House 1	58.7%	57.6%
	House 2	64.1%	58.0%
	House 3	64.8%	63.5%
	House 4	61.9%	56.9%
	Average	**62.4%**	**59.0%**
Latent Effectiveness	House 1	52.6%	52.5%
	House 2	53.8%	53.7%
	House 3	57.1%	55.7%
	House 4	50.5%	50.8%
	Average	**53.5%**	**53.2%**
Total Effectiveness	House 1	55.7%	57.1%
	House 2	58.1%	58.4%
	House 3	61.3%	62.0%
	House 4	56.4%	56.6%
	Average	**57.9%**	**58.5%**

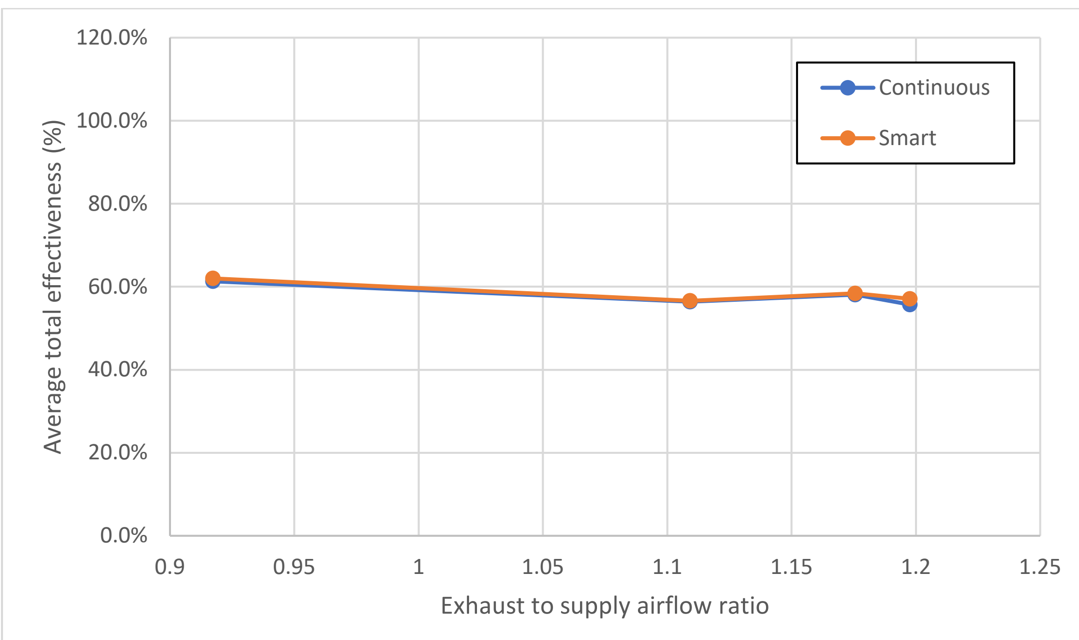

Figure 42. Test home ERV exhaust to supply airflow ratio vs. average total effectiveness

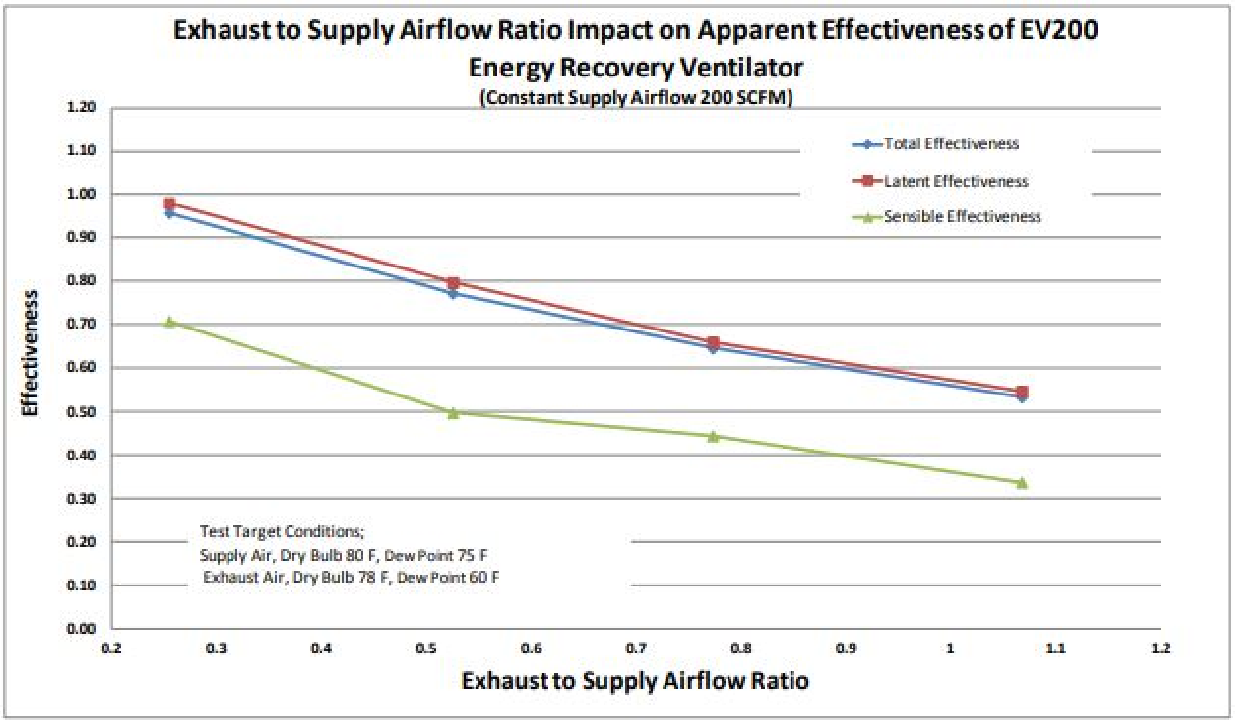

Figure 43. Lab-tested ERV effectiveness at high outdoor humidity conditions vs. various exhaust to supply airflow ratios

Source: Kosar (2016), Figure 11

The variation in ERV effectiveness by season can be seen in Table 50 and is visualized in Figure 44 through Figure 46. Total effectiveness is highest in winter and lowest in summer, as is apparent sensible effectiveness. Total effectiveness varies by about ±6.5%, whereas apparent sensible effectiveness varies by about ±20%. Latent effectiveness is highest in summer and lowest in winter but is the most seasonally consistent throughout the year (±3.5%). The differences between smart mode and continuous mode are marginal and are most likely due to sampling period differences and variations in sensor accuracy rather than actual performance.

Table 50. Test Home Seasonal ERV Effectiveness Results

		Spring		Summer		Fall		Winter	
	House	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**	**Continuous Mode**	**Smart Mode**
Apparent Sensible Effective-ness	House 1	53.0%	46.2%	37.6%	37.1%	65.8%	68.8%	78.4%	78.3%
	House 2	59.0%	51.9%	37.9%	35.3%	77.5%	63.8%	81.8%	81.1%
	House 3	60.6%	54.3%	46.5%	43.6%	70.8%	76.3%	81.2%	79.8%
	House 4	59.5%	53.7%	40.8%	37.6%	72.6%	62.9%	74.6%	73.3%
	Average	**58.0%**	**51.5%**	**40.7%**	**38.4%**	**71.7%**	**68.0%**	**79.0%**	**78.1%**
Latent Effective-ness	House 1	49.7%	51.5%	53.0%	53.2%	55.1%	54.0%	52.5%	51.1%
	House 2	51.2%	53.6%	55.8%	56.2%	55.0%	54.9%	53.2%	49.9%
	House 3	55.1%	57.6%	60.6%	60.7%	56.9%	53.3%	55.8%	51.3%
	House 4	48.4%	51.7%	55.1%	55.1%	50.6%	51.3%	48.0%	45.1%
	Average	**51.1%**	**53.6%**	**56.1%**	**56.3%**	**54.4%**	**53.4%**	**52.4%**	**49.4%**
Total Effective-ness	House 1	53.2%	51.0%	50.1%	50.4%	58.6%	62.8%	60.8%	64.1%
	House 2	55.9%	52.6%	51.8%	51.5%	58.4%	61.5%	66.2%	68.1%
	House 3	59.2%	58.6%	57.9%	57.3%	61.8%	65.4%	66.1%	66.7%
	House 4	53.2%	53.4%	52.1%	50.9%	57.6%	58.4%	62.6%	63.7%
	Average	**55.4%**	**53.9%**	**53.0%**	**52.5%**	**59.1%**	**62.0%**	**63.9%**	**65.7%**

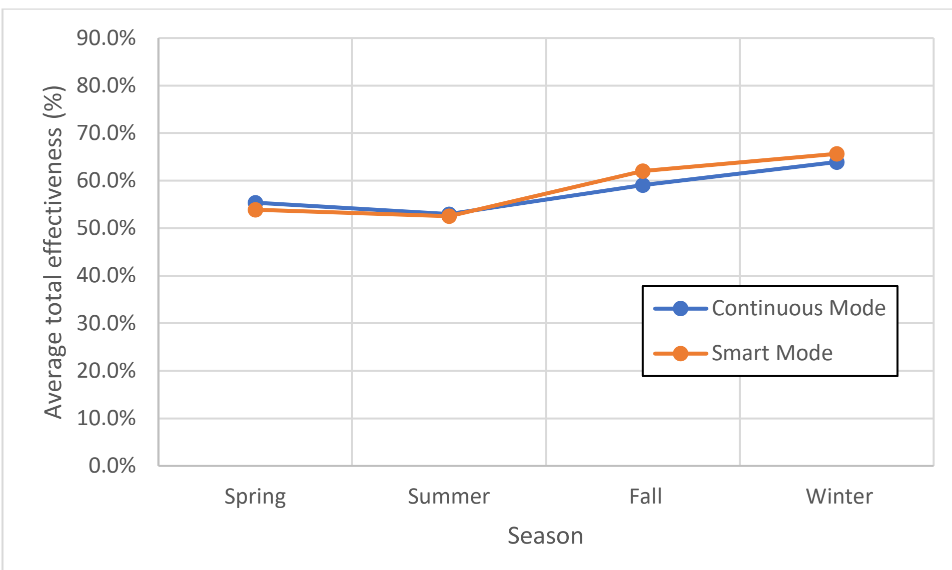

Figure 44. Average test home ERV total effectiveness by season

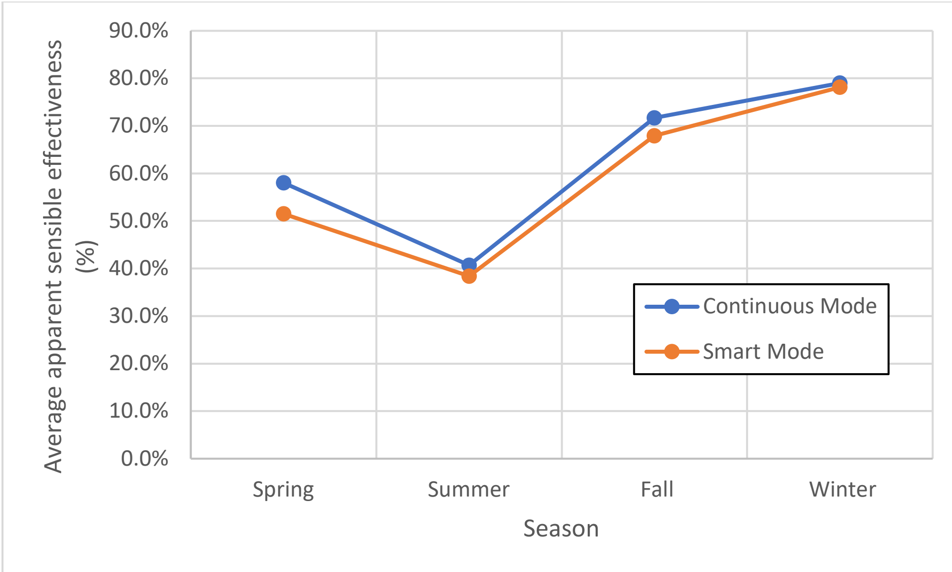

Figure 45. Average test home ERV apparent sensible effectiveness by season

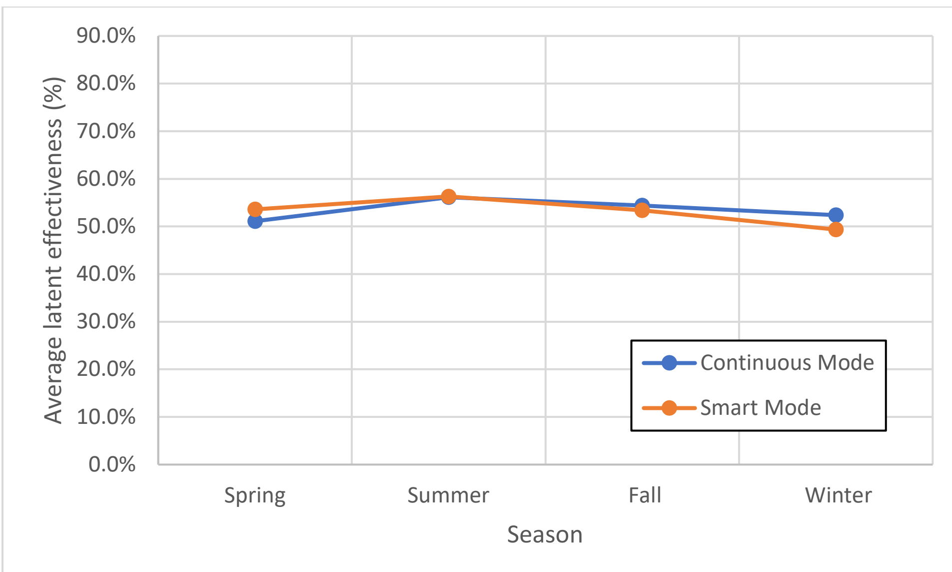

Figure 46. Average test home ERV latent effectiveness by season

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